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**13. ABSTRACT** *(Maximum 200 words)*

Aviation and ground systems must increase use of emerging and advanced technologies to remain viable in complex, future battlefield environments. Unmanned vehicles will become part of future military operations due to: the demand for immediate intelligence on the battlefield, decreasing defense budgets, increasing operational tempos, and the low tolerance for casualties by the public. This work develops and evaluates system level concepts that fulfill these overall requirements using an unmanned hybrid vehicle. The unmanned hybrid vehicle combines the attributes of an autonomous vertical takeoff and landing air vehicle and an autonomous ground vehicle. This allows fast, flexible deployment and quiet, longer duration ground missions. The assumed time of deployment is the year 2012. The study included requirements definition, concept synthesis, and down selection to three final configurations. Engineering students from the University of Alabama in Huntsville and Ecole Supérieure des Techniques Aéronautiques et de Construction Automobile participated on three competing design teams. Team 1 developed a basic system with coaxial rotors and a fuel cell drive system. The system is one unit that can both fly and operate on the ground. Team 2 developed a separate air and ground vehicle with intermeshing rotors. The integrated ground unit is deployed and retrieved by the air system. Team 3 also developed a separate air and ground vehicle but with a single rotor system that also requires a tail rotor.

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# Unmanned Hybrid Vehicle

## Final Report – Volume II
## IPT 1

Submitted By:

# UAH Integrated Product Team 2002

# IPT 002

**Authors: Jamie L. Flynt, Geof F. Morris, Dana M. Quick, Jennifer C. Pierce, and Robert A. Frederick, Jr**

**Contract DAAH01-01-C-R160 Option Order 25**

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# Final Proposal:
# Unmanned Hybrid Vehicle

# IPT 1

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April 25, 2002

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|---|---|
| Army Aviation and Missile Command | Ecole Superieure des Techniques Aeronautiques et de Construction |
| The University of Alabama in Huntsville | The American Helicopter Society |
| Snecma | Quality Research |
| Sigma Services of America | HDC |
| SAIC | Sandia National Laboratory |

**The University of Alabama in Huntsville**
**April 25, 2002**

# Executive Summary

## English

Due to increasing technological advances in the global militaries, the field of gathering information is quite imperative for survival. The Choctaw is a UHV (Unmanned Hybrid Vehicle) capable of retrieving information about the adversary by performing air and ground missions set forth by AMCOM (The United States Army Aviation and Missile Command) in a Conceptual Design Document (CDD). The Choctaw will be available for deployment in the year 2012 after extensive research. The company responsible for this vehicle design is J5 Engineering. J5 Engineering is composed of students from the University of Alabama in Huntsville (UAH) and ESTACA, an engineering university located in Paris, France.

## French

En raison de l'avancée des technologies, l'arme la plus puissante est désormais le renseignement. Il permet aux stratèges de l'armée d'opérer sur un champ de bataille sans risquer la vie de leurs hommes. La reconnaissance et l'espionnage sont les moyens les plus fiables pour récupérer des informations. Dans cette optique l'équipe *J5 Engineering*, formée par des étudiants de l'Université d'Huntsville dans l'Alabama (UAH), et de l'Ecole Supérieure des Techniques Aéronautiques et de Construction Automobile (ESTACA), travaille à la mise en oeuvre d'un concept de drone hybride, dont le cahier des charges est fixé par l'AMCOM (The United States Army Aviation and Missile Command).

Pour répondre à ce cahier des charges, J5 Engineering a mis au point le Choctaw. Ce drone doit être opérationnel en 2012.

# UHV Compliance List

The following list details the location of all specification compliances for the UHV. The list shows the location in the CDD, located in Appendix A, provided by the Army of every specification and the section where that specification is dealt with in this proposal

CDD location:                                                    Proposal location:

## General Description of Operational Capability

# System Capabilities

# Table of Contents

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# Common Terms and Acronyms List

| Word | Comments |
|---|---|
| AGL | Above Ground Level |
| AGL | Above Ground Level |
| AIAA | American Institute of Aeronautics and Astronautics |
| AMCOM | United States Army Aviation and Missile Command |
| BLOS | Beyond Line of Sight |
| CAD | Computer aided design |
| CM | Communication |
| Concept Description Document | Document that details the customer's technical specifications for the UA/UGV |
| CST | Central Standard Time |
| EE | Electrical Engineering |
| EH | English |
| EM | Engineering Management |
| EST | Editorial Support Team |
| ESTACA | Ecole Superieure des Techniques Aeronautiques et de Construction Automobiles |
| FLOBT | Forward Line of Battlefield Troops |
| Ft | feet |
| IPT | Integrated Product Team |
| IRP | Intermediate Power Rating |
| km | Kilometer |
| lbs. | Pounds |
| MAE | Mechanical and Aerospace Engineering |
| MKT | Marketing |
| MSFC | Marshall Space Flight Center |
| nm | Nautical miles (~2025 yards) |
| Payload | Item carried by the system having a specified weight |
| TBD | To be determined (not know at this time) |
| TBE | Teledyne Brown Engineering |
| TF/TA | Terrain following/terrain avoidance |
| UAH | The University of Alabama in Huntsville |
| UAV | Unmanned Air Vehicle |
| UGV | Unmanned Ground Vehicle |
| UHV | Unmanned Hybrid Vehicle |
| VROC | Vertical rate of climb |
| VTOL | Vertical takeoff and landing |

# Team-Specific Terms and Acronyms List

| Word or symbol | Comments |
|---|---|
| C | Capacitance of the complete ultracapacitor stack at its operating point |
| $C_D$ | Drag Coefficient |
| $C_L$ | Blade Lift Coefficient |
| $C_o$ | Root Chord |
| $C_t$ | Tip Chord; Torque in Transmission |
| d | Inside diameter of a shaft in the transmission system |
| D | Vehicle Drag; Outside Shaft Diameter in Transmission |
| Dn | Pitch diameter of the gear n in the transmission system |
| dV | Change in voltage during the discharge of the capacitor |
| E | Output energy of a cell |
| Er | Required energy for the fuel cell |
| Es | Energy provided by a PEM fuel cell with 1kg of hydrogen |
| Ft | Tangential force on the pitch radius of the conic gear |
| i | Electric current in the ultracapacitor |
| k | Coefficient of the teeth width |
| L | Lifting Force |
| m | Module of the gear |
| mH2 | Hydrogen mass |
| Nmax | Max rotation speed of the shaft in the transmission system |
| Nn | Number of teeth of the gear n in the transmission system |
| Nparallel | Number of individual capacitors in parallel |
| Nseries | Number of individual capacitors in series |
| $\rho$ | Density |
| P | Total power to provide to the UHV; Power to provide to the ultracapacitor |
| Pavionic | Power to provide to the avionic |
| $P_c$ | Power Required to Climb |
| $P_f$ | Min Power for Forward Flight |
| Pground | Power to provide to the ground system |
| $P_h$ | Power Required to Hover |
| Pm | Maximum power of the shaft engine in the transmission system |
| Pmax | Max power required by the ultracapacitor |
| Pt | Power of the shaft engine of the transmission system |
| R | Resistance of the complete ultracapacitor stack |
| Rcell | Cell resistance |
| r2 | Reductions ratios of the transmission system |

| | |
|---|---|
| r1 | Reductions ratios of the transmission system |
| r | Efficiency of a fuel cell |
| S | Planform Area of Blade |
| $T_h$ | Thrust for Hover |
| V | Vehicle Air Speed |
| $V_c$ | Cruise Speed |
| Vcel | Cell voltage |
| $V_{fs}$ | Free Stream Velocity (tip speed + vehicle speed) |
| Vw | Operating voltage at the beginning of a discharge of an ultracapacitor |
| Vmin | Minimum voltage allowed by the ultracapacitor |
| Vmax | Max voltage required by the ultracapacitor |
| we | Shaft speed input in the transmission system |
| ws1 | Shaft speed output for the rotor 1 in the transmission system |
| ws2 | Shaft speed output for the rotor 2 in the transmission system |
| Zn | Number of teeth of the conic gear n |
| V | Volume of hydrogen (Fuel Cell) |

# IPT 1: Feasibility of Unmanned Hybrid Vehicle

## 1.0 UHV – Unmanned Hybrid Vehicle

### 1.1 The Need

Modern battlefields capitalize on one major weapon previously unavailable to battlefield commanders: total information. Reconnaissance and intelligence gathering is a rapidly-growing battlefield need, and with communications systems now available to transmit all battlefield data to all combatants on a side, the hunger for information is growing exponentially. Reconnaissance missions, however, are extremely dangerous for their crews, as these missions often involve being near or behind the enemy's Forward Line of Battlefield Troops (FLOBT).

With this need for information and the resultant edge on the battlefield comes the desire to conduct reconnaissance missions remotely. In steps the concept of an Unmanned Hybrid Vehicle (UHV), which can maneuver on the ground and in the air to survey the battlefield and report information back to the commander. The United States Army's Aviation and Missile Command (AMCOM) has charged students at The University of Alabama in Huntsville (UAH) and Ecole Superieure des Techniques Aeronautiques et de Construction Automobiles (ESTACA) that participate in the Integrated Product Teams (IPT) design class with developing ideas for a first-generation UHV that can operate at least semi-autonomously on the battlefield, gathering information and performing ancillary missions as needed.

### 1.2 The Requirements

Requirements set by the customer, the U. S. Army Aviation and Missile Command (AMCOM), were provided in a Concept Description Document agreed upon by the customer and all competitors prior to the beginning of the design competition.

The UHV must perform both air and ground missions in its overall flight profile. The UHV must travel a minimum of 15 km beyond the FLOBT at an airspeed of no less than 30 km/hr in 30 minutes. The UHV must then perform a ground mission of two hours at a ground speed of no less than 6 km/hr while traveling in a radius of no less than 0.5 km from the landing site. The ground mission includes transporting a payload of no more than 120 lbs. The UHV must then perform another air mission to return home in 30 minutes or less.

The UHV was given specified physical characteristics. The total system weight should not exceed 1500 lbs. while designed to be transported via a HMMWV and trailer and/or via sling load by a UH-60 helicopter.

The key challenges of this design project involve merging the ground and air portions of the system. With current UAV's having fixed wings and UGV's having tracks, combining the two vehicles into one and placing additional transportation requirements that limit the overall size of the vehicle make this design challenging.

## 1.3 The Solution

### 1.3.1 Concept Overview

Figure 1 shows an artist's conception of the Choctaw UHV as designed and conceived by J5 Engineering. The Choctaw UHV is a coaxial rotorcraft driven by four independently powered, electrically driven wheels that are fixed below the main part of the pistachio-shaped fuselage. Figure 2 shows more details regarding the placement of features in the Choctaw UHV, including the forward sensor array, the servo-flaps on the rotors, and the drop-down doors that allow crew access to the payload bay. A crewman is pictured in both conceptions to give a notion of the size of the vehicle.
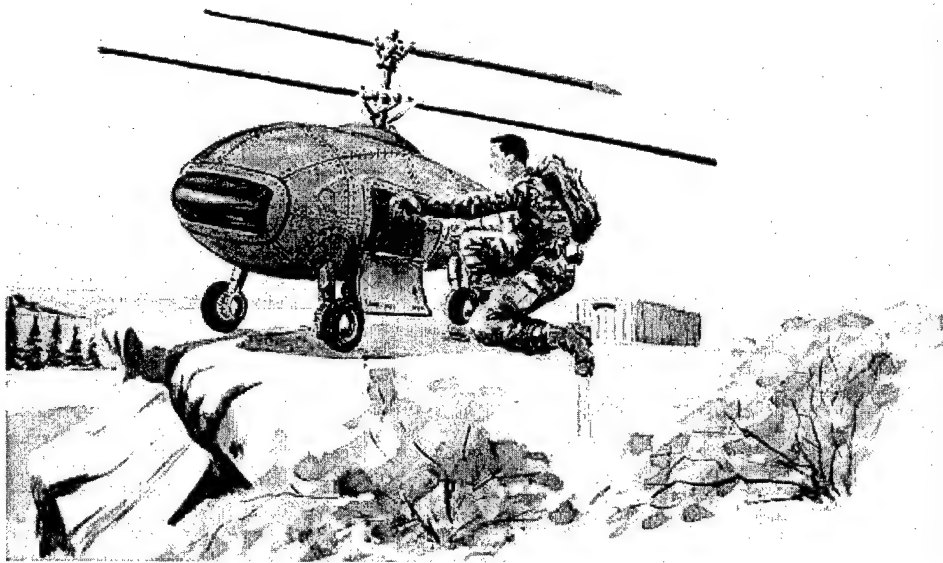


Figure 1: Artist's Conception of Choctaw UHV
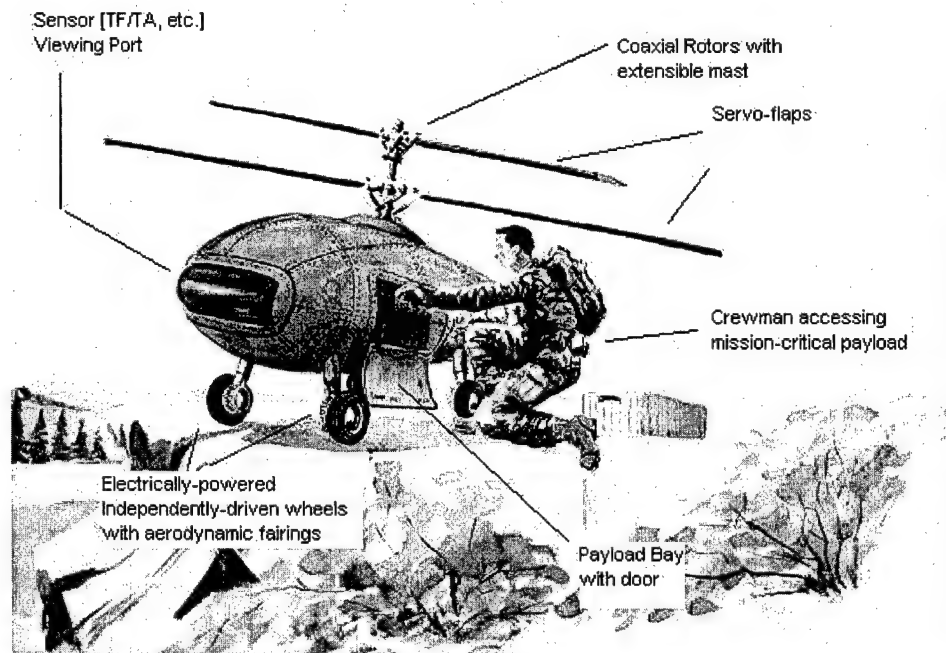
Figure 2: Artist's Conception with Externally Visible Features Highlighted

### 1.3.2 Dimensional Properties

Figure 3 shows the dimensional properties of the vehicle and approximate locations for the various major subsystems that will effect the mass and center of gravity (CG) balance of the Choctaw UHV. [Note: These files are individually produced, and as such are so large that size reduction makes any notations on them illegible. Figure 3a is a cross-sectional view.]

50in

5in

45in

84in

45in

Center of Gravity    Points of attachment for sling

4
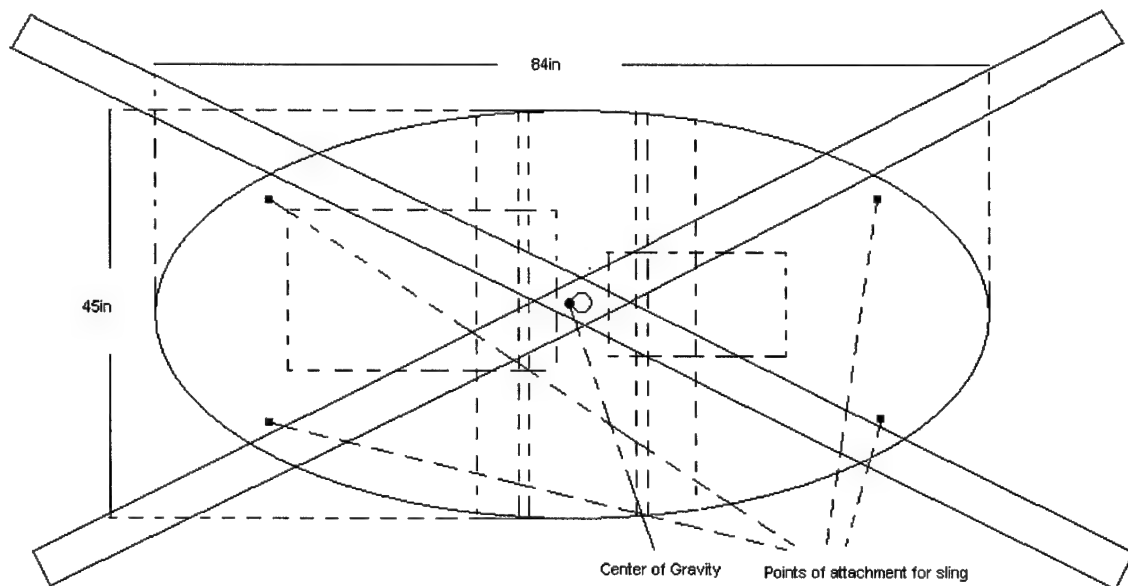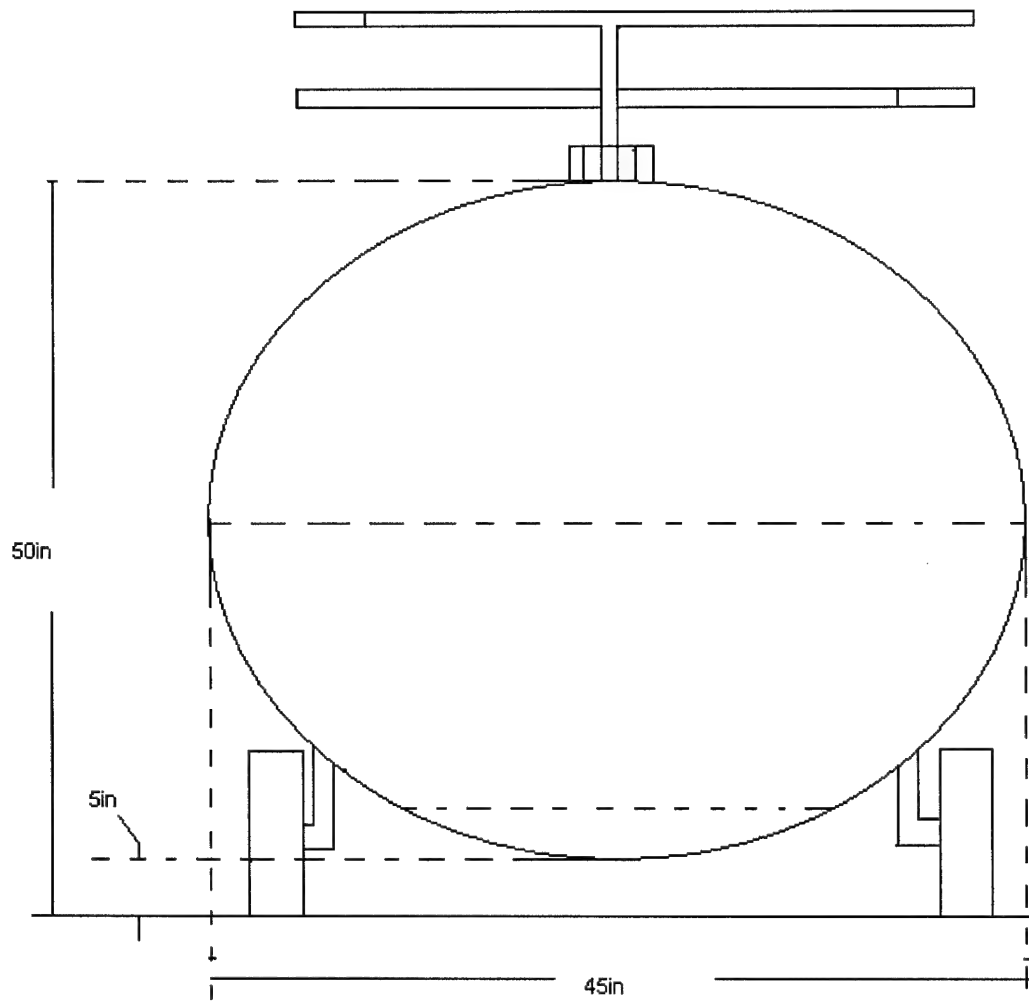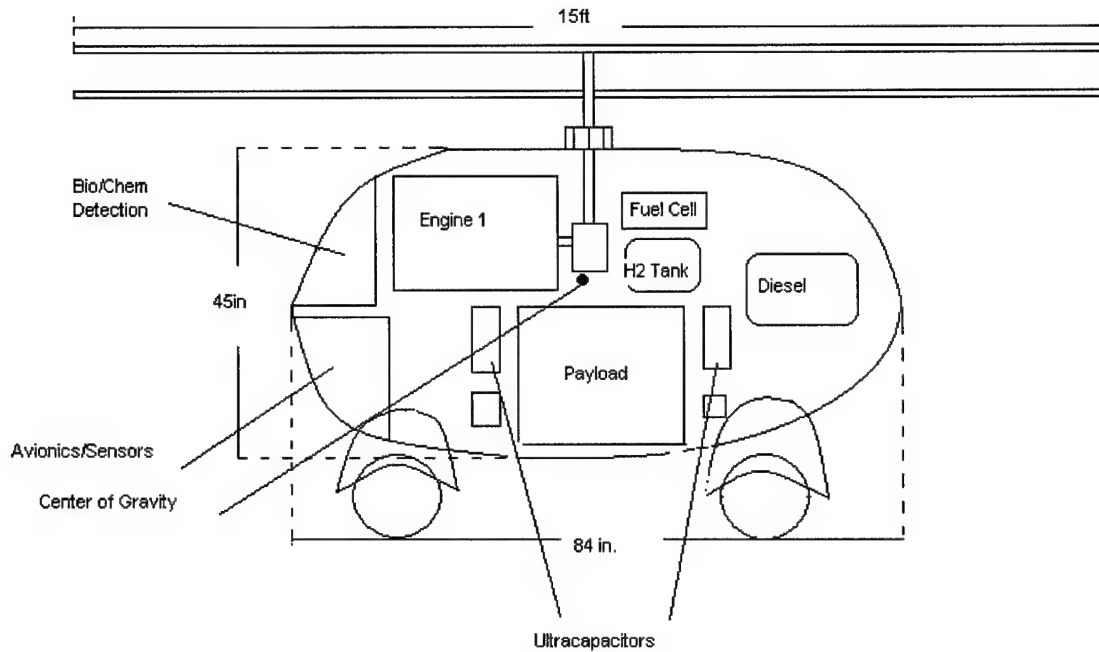
Figure 3: Three-View Drawing

### 1.3.3 Operations Scenario

The baseline mission profile as outlined in Figure 4 shows the expected mission of the Choctaw UHV as outlined by the customer in the CDD. Segment 1 begins with engine start. Segment 2 is a transitional go/no-go phase after the engine has warmed up. Segment 3 involves a vertical climb to the operational altitude of 0-250 ft above ground level (AGL). Segment 4 is an outbound cruise leg at the operational altitude at a speed of at least 30 km/hr. Segment 5 is a landing phase. Segment 6 involves hovering prior to touchdown. The air phase of the mission must be able to take place in one (1) hour.

Segment 7 is the ground phase of the mission: a 0.5 km radius from the touchdown point must be covered at a speed of no less than 6 km/hr over the ground. The ground mission is to take at least two (2) hours.

Segments 8-12 involve repeating the air phase as before with the same requirements. At landing in Segment 12, the vehicle must have an operational fuel reserve of 10%.

**Critical Flight Conditions:**
Altitude - 4000 ft
Temp - 95°F
VROC – 200-500 FPM

**Segment 4**
Cruise Outbound
ALT NOE-250 ft
Velocity 0-30 km/hr
Range 15 km

**Segment 10**
Cruise Inbound
ALT NOE-250 ft
Velocity 0-30 km/hr
Range 15 km

**Segment 3**
Climb to Combat Operational Altitude
VROC 200 FPM

**Segment 9**
Climb to Combat Operational Altitude
VROC 200 FPM

**Segment 5**
Descend

**Segment 11**
Descend

**Segment 1**
Engine Start
Warm Up

**Segment 7**
Ground Maneuver
Radius 0.5 km

**Segment 2**
Hover

**Segment 6**
Hover and Land

**Segment 8**
Repeat Segments 2-7 as Required

**Segment 12**
Hover
Land
10% Fuel Reserve

Figure 4: Operations Scenario

The Choctaw UHV could perform many iterations of this flight/ground regime given design constraints. Larger fuel tanks could be provided, as the vehicle is under the maximum gross allowable weight of 1500 lbs. If more diesel fuel and hydrogen can be provided for the vehicle, multiple missions could be performed before refueling (and refitting, as necessary) must be done.

## 1.4 The Performance

The Choctaw performs the air and ground mission required from the CDD (Appendix A). Using "worst case scenarios,"J5 designed a light vehicle to meet the requirement given by AMCOM. Using Fuel Cells (FC), this vehicle does not meet the CDD requirements for the ground mission but the trade-off analysis will prove this is superior to the Internal Combustion Engine (ICE). The FC concept is presented in this report as the ICE is described to Appendix C2.

Table 1: Final Concept Evaluation – Baseline Mission Profile

| CDD Requirement | Requirement | Assessment | Remark |
|---|---|---|---|
| Payload | 60 lbs | **60 lbs** | **Meets Specification** |
| Endurance | 4 hours | **4 hours** | **Meets Specification** |
| Flight Profile | Hover-Full | **Hover-Full** | **Meets Specification** |
| Vertical Climb | 200 fpm | **200 fpm** | **Meets Specification** |
| Operational Altitude | 0 – 250 ft AGL | **0 –250 ft AGL** | **Meets Specification** |
| Air Speed | 30 km/hr | **30 km/HR** | **Meets Specification** |
| Ground Speed | 6 km/hr | **6 km/hr** | **Meets Specification** |

| Operation | Semi-autonomous | Semi-autonomous | Meets Specification |
|---|---|---|---|
| Communication | BLOS | BLOS | Meets Specification |
| Transportable | HMMWV, UH-60 | HMMWV, UH-60 | Meets Specification |
| Max System Weight | 1500 lbs | 1321.66 lbs | Below Max |
| Deployment | 2012 | 2012 | Meets Specification |
| Acoustic Profile | Near-quiet | Near-quiet | Meets Specification |
| Fuel | Jet or Diesel Fuel | ICE Concept | Meets Specification |
|  |  | FC | Does Not Meet Specification |

## 1.5 The Implementation

Table 2 lists the implementation schedule for the Choctaw UHV. Technological development on the fuel cells and avionics/sensors to be used by the Choctaw UHV will be considered during the technological development timeframe, as well as an overall review of possible design improvements in the vehicle. Delivery is anticipated in FY 2012.

Table 2: Programmatic 10-Year Development Schedule

| Task | Year Completed |
|---|---|
| Contract Negotiation | 2002 |
| Technological Development/ Prototype Run | 2003-2005 |
| Testing of Initial Prototype | 2006 |
| Redesign Reflecting Test Results | 2007 |
| Manufacturing Run | 2008-2012 |

## 2.0 Technical Description of Methods Used

The various technical discipline leads have explained the methods they employed in their technical approach to the design of this concept. That information will be found in the succeeding paragraphs of Section 2.0.

## 2.1 System Engineering

### 2.1.1 Design Philosophy

J5 Engineering wanted to achieve all desired requirements set for by the customer. Due to the potential application of this vehicle, some requirements had more influence than others.

For instance, a low acoustic signature is very important in any surveillance situation. Also possessing essential performance characteristics under adverse weather conditions is very significant to the survival of our vehicle (Appendix A). This design, however, centers on mission completion without detection.

After the initial Baseline concept, J5 further continued the design of the Rolling Feather. The Alternative phase yielded three possible concepts: the "Fighting Duct", the "Choctaw", and the "Seagull". J5 chose to pursue further the Choctaw design, which is a variation of the Baseline. Given the requirements from the customer, J5's version of the improved "Rolling Feather" differed by having fuel cells, automatic-folding blades, and four motorized wheels.

The initial characteristics of the Choctaw were the following: 15 ft. folding coaxial blades, a hybrid propulsion system using fuel cells and an electric motor, four motorized wheels powered by the electric motor, and payload situated in the back of the craft. Sensor and navigation avionics such as TF/TA Radar and GPS electronics were chosen.

The final concept includes most of the previous characteristics, but improved configurations. Spring-loaded coaxial blades with servo flaps; a hybrid propulsion system consisting of fuel cells, electric motor, and ultracapacitors; four motorized wheels; and payload situated near the center of the vehicle.

## 2.1.2 Design Processes

"Worst case" scenarios were used to design both the air and ground characteristics. The team from France designed the hybrid propulsion system consisting of fuel cells and electric motors. Guidelines for choosing the system include a near quiet acoustic signature, capability of having a VROC of 200 fpm, weight and size constraints, and using available diesel or jet fuel. Though fuel cells do not use the fuel mentioned, the trade off is considerable.

Fuel cells are known to have near quiet acoustic signature and are fairly lightweight compared to the larger engines needed to produce the VROC. This is significant in detection. Also, current technology is increasing rapidly in producing lighter fuel cells. Car manufacturers are designing concept cars with the future use of fuel cells in mind.

One major disadvantage of fuel cells is the availability of hydrogen for the "fuel". With the increasing technology, J5 feels hydrogen will become more available by the year 2012. And though highly flammable, canisters were found that could hold hydrogen with only minor leakage when fired upon by ammunition.

An electric engine is chosen for the ground mission. It easily powers the motorized wheels. Another notion selected is the use of ultracapacitors. Ultracapacitors are selected because they can provide an additional source of energy for the propulsion system. They allow optimal tailoring of propulsion systems by providing no more (or less) than the power needed.

Guidelines for the aerodynamic portion of the vehicle include the following: low weight, aerodynamic characteristics, and large enough to propel 1500 lbs. The aerodynamic team leader researched the use of folding coaxial blades. The length and aspect ratio stayed the same at 15 and 18 ft, respectively. Spring-loaded blades and servo flaps were chosen, decreasing the use of avionics and electricity needed to provide a viable design.

The ground mission team leader suggested using four motorized wheels. Due to the adverse ground and weather conditions, J5 feels this is the best choice for completing this portion of the mission. These wheels are light enough to complete the air mission as well. It is also advantageous to have this design to operate in small spaces.

The payload in the initial design was placed in the back of the vehicle with a hatch for access. The Mechanical Configuration department found a payload positioned near the center of the vehicle with through-hole roll doors located on both sides of the vehicle to be most desirable due to weight balance and survivability.

## 2.2    Aerodynamics

### 2.2.1   Introduction

The basic design of our final vehicle is a co-axial rotorcraft much like the one presented in the baseline design. In this design, two main rotors are used on the same shaft. One rotor will turn clockwise, while the other will rotate counter-clockwise. The motion of one-rotor disk counters the torque produced on the vehicle by the other rotor disk. This eliminates the need for a separate, torque-countering device such as a tail rotor and thus conserves space. Another advantage of the co-axial design is that now all the power is sent directly to the lifting devices rather than having to waste power on a separate, counter torque device. Although the basic design is very similar to the baseline concept, several aerodynamic enhancements have been made that improve the performance of the Choctaw over the baseline.

The largest enhancement made to this vehicle versus the baseline design is the overall vehicle weight. By reducing the weight of the vehicle, less power is required from the propulsion system in order to provide the same performance characteristics. Enhancements over the baseline were also made to the rotor system, which will increase the performance of the vehicle. These enhancements were geared at both the rotor blades as well as the rotor hub.

### 2.2.2   Rotor and Blade Design

The main goal aerodynamically was to retain a low weight estimate for the vehicle and increase the overall aerodynamic performance of the vehicle. To accomplish this in the design of the rotor blades, we used composite materials, which are high in strength and low in weight. By hollowing out the inside of the blades and placing spars at even spaces along the span, a minimal weight can be obtained without compromising the structural stability. The Boeing Company manufactures the airfoil chosen for this design. The VR –15 has been selected from the Boeing Vertol series (Leishman 2000). This particular airfoil offers an

adequate compromise between maximizing the lift capability of the blades and maximizing the drag divergence at various Mach numbers. As can be seen in Figure 5, the slight camber at the nose of the airfoil helps to increase lift while the low blade thickness helps to reduce drag (Leishman2000). Also, the blade design is simple and robust and will be adequate for the combat environment. By giving the blades an aspect ratio of 18, the maximum lift at limited power can be achieved without compromising the structural stability of the blades.

VR-15

Figure 5: Boeing Vertol VR-15 Airfoil

In order to determine the optimum disk area for this design, calculations were done that compared the required power output to the size of the rotor. The approach for co-axial rotorcraft is to assume that each rotor disk is responsible for half of the total lift required. The basic equation to determine the required power for hover for each rotor disk can be seen in Equation 1 below (Berry 2002).

$$P_h = \sqrt{\frac{T_h^{\;3}}{2\rho A_D}}$$
Equation 1

Table 3 lists the parameters used in the equation above. For hover, the required thrust is simply equal to that of the vehicle weight. It is a fairly accurate, static calculation. The same basic equation is also used to calculate the power required for climb and forward flight. However, when vehicle motion is present, lift and drag of the vehicle and rotor blades have to be taken into account. Therefore, in order to calculate the power requirements for climb and forward flight, several complex spreadsheets were utilized (Berry 2002). The results for hover and climb can be seen in Figure 6.

Figure 6 below represents the effects of disk area on required power. The figure helped the design team to determine a suitable rotor disk radius of 7.5 ft. By maintaining a rotor diameter of 7.5 ft, an adequate amount of thrust could be generated from the rotor disk without demanding too large of a power output from the propulsion system. As can be seen from Equation 1, required power is a direct function of the size of the rotor disk. The larger the rotor disk, the more thrust can be generated at lower engine power. By retaining a less powerful propulsion system, the design team is able to keep the overall vehicle weight down.
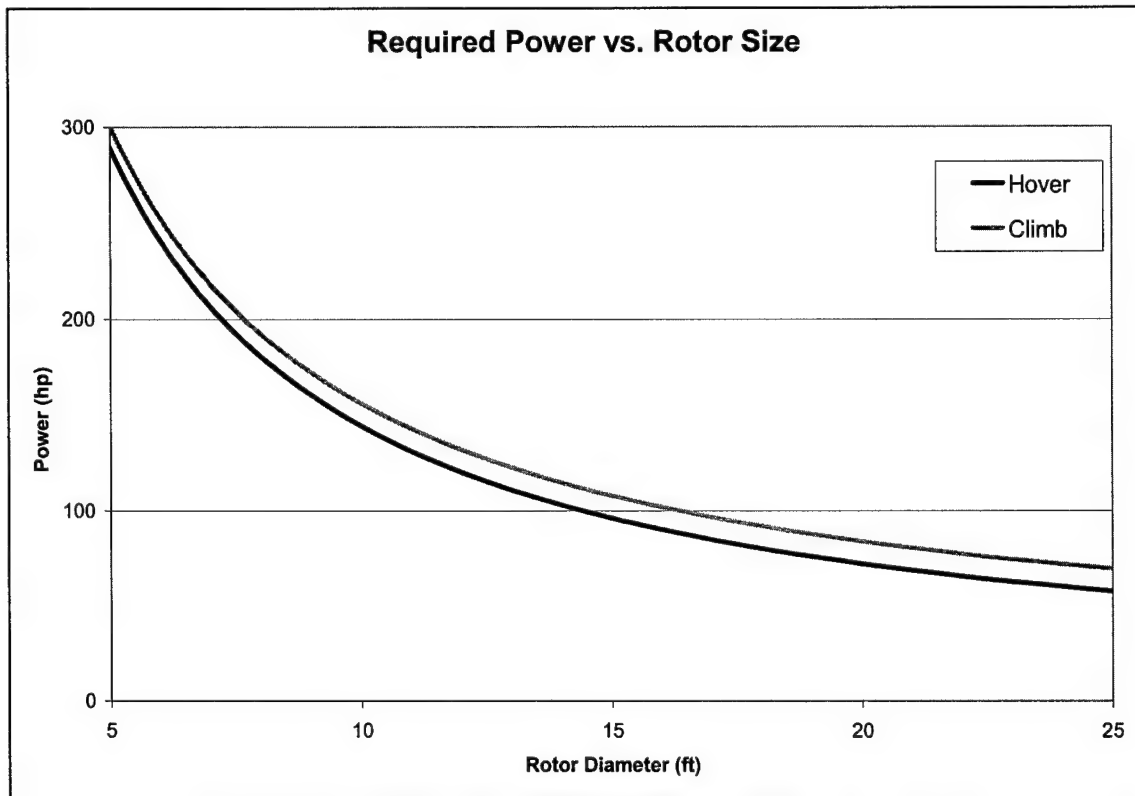
Figure 6: Required Power vs. Rotor Size

Once the rotor radius had been determined, it was necessary to calculate the power profile of the vehicle in forward flight. Rotorcrafts are unique in that there is a minimum power requirement at a precise positive forward speed. As the vehicle moves forward through the air, the rotor blades start to generate lift. Depending on the pitch of the blades, the vehicle is partially propelled through forward flight simply by the aerodynamic forces acting on the blades. Thus, the aerodynamic forces can be utilized to help reduce the power requirements on the propulsion system.

Figure 7 represents the flight profile for this design. As can be seen, a trough exists in the plot that indicates the optimum forward speed at minimum power. At the trough, the lift generated by the blades adds to the performance of the vehicle in flight. Pressure and friction drag start to play a more important role as vehicle speed increases.
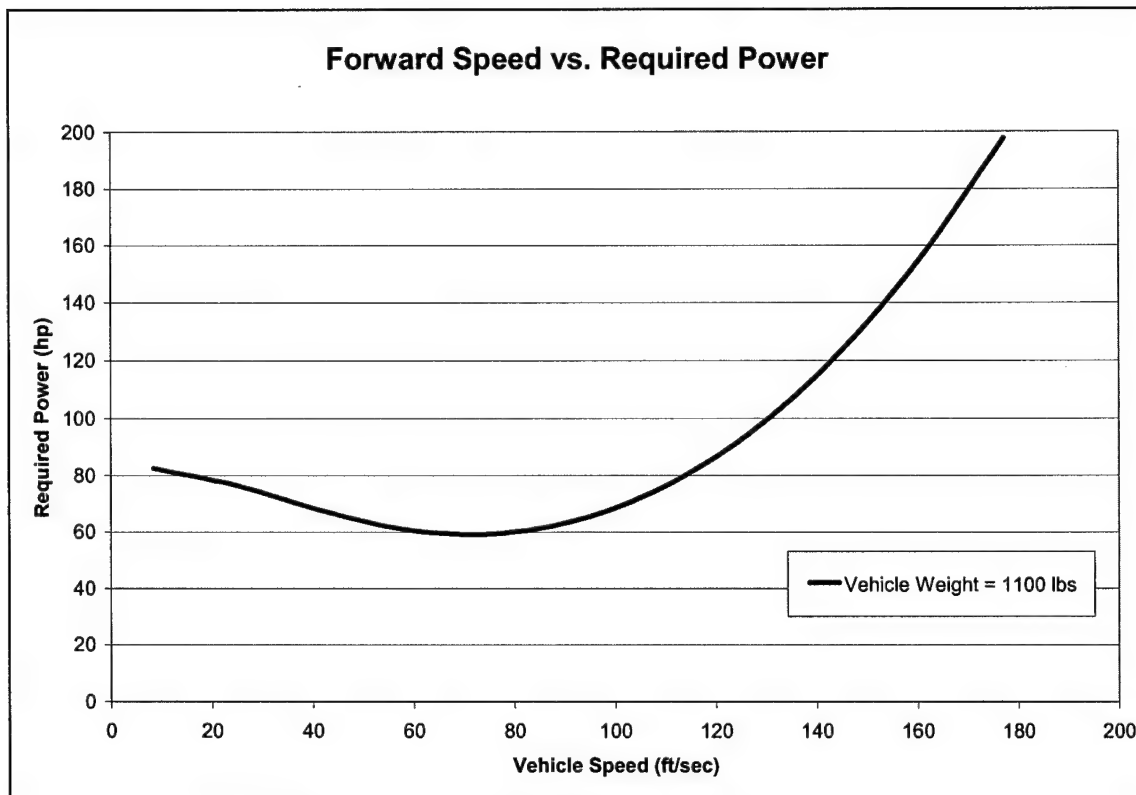
Figure 7: Vehicle Forward Speed v. Required Power

It should be noted that certain assumptions were made in obtaining the calculations presented thus far. The rotor tip speed is assumed constant at 650 ft/sec. A tip speed in this range ensures that the blades will not encounter supersonic flow throughout the flight profile. Thus, compressibility, particularly on the blade tips, can be ignored. The environment was assumed to be static at a temperature of 95 degrees F and an elevation of 4000 ft. This provided a 'worst case' scenario and enabled the design team to predict the maximum power requirements. The last assumption made was on the exact drag coefficient of the vehicle. The coefficient was assumed to be at 1.2. This provided a modest estimate that would allow the design team to gain solid estimates for the calculations presented in this section. Without proper wind tunnel testing, it is difficult to calculate a precise drag coefficient.

A basic summary of the blade specifications and the aerodynamic performance analysis can be seen in Table . These values were used to determine the power plant selection of the vehicle as well as the overall weight calculations of the vehicle. It is of interest to note that a figure of merit has already been implemented into all the power calculations. The figure of merit, equal to 0.8, accounts for the inefficiencies of the propulsion system to transfer all of its power to the rotor shaft and eventually to the rotor disk.

Table 3: Summary of Aerodynamic Calculations

| Airfoil | Boeing Vertol series VR-15 |
|---|---|
| Rotor Length (b) | 7.5 ft |
| Rotor Disk Area ($A_D$) | 176.71 ft$^2$ |
| Aspect Ratio | 18 |
| Root Chord ($C_o$) | 0.4167 ft |
| Tip Chord ($C_t$) | 0.4167 ft |
| Density ($\rho$) | 1.078 kg/m$^3$ |
| Thrust for Hover ($T_h$) | 550 lbs per rotor |
| Power Required to Hover ($P_h$) | 96.21 hp |
| Power Required to Climb ($P_c$) | 107.96 hp |
| Cruise Speed ($V_c$) | 75.95 ft/sec |
| Min Power for Forward Flight ($P_f$) | 59.39 hp |

There is a significant problem with forward flight that is unique to all rotorcraft. The vehicle will have a tendency to yaw and roll in the direction of the retreating blades. The root of this problem lies in the fact that the advancing blades are actually experiencing a higher free stream velocity than that of the retreating blades. Thus, a greater aerodynamic lifting force is being exerted on the side of the vehicle with the advancing blades. Although this problem is somewhat reduced by the fact that the design of this vehicle has two, counter-rotating blades, it still presents a control issue. In order to correct this problem, a fully articulated hub for both rotor disks has been implemented. The articulated hub offers independent flapping hinges for each rotor blade. Figure 8 below gives a solid representation of a typical hub with flapping hinges (http://www.helis.com/howflies/servo.htm). This figure was taken from a Kaman rotorcraft but closely resembles the design of the Choctaw.
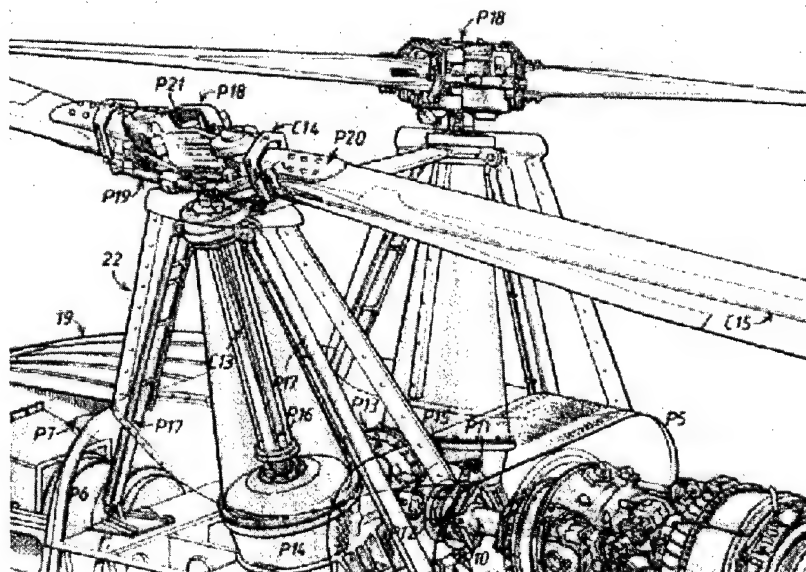


Figure 8: Rotor with Flaps, Kaman Rotorcraft

This will allow the blades to effectively pivot about the hinge and raise or lower as necessary without actually changing the orientation of the main body of the vehicle. Another advantage of using flapping hinges at the hubs to connect the blades is that the blades are allowed to move without having to flex or bend. This will effectively increase the service life of the blades.

However, this solution required consideration of another design aspect. Since this design presents one rotor disk on top of the other, it was important to know exactly how much the blades would lower or raise depending on free stream velocity that each is experiencing so that no collision would occur. To do this, the additional lift had to be calculated over the advancing blade. Equation 2 below was used to perform this calculation.

$$L = .5\rho V_{fs}^{2} S C_{L}$$
Equation 2

Table 4 below defines the parameters used in this equation. It is of interest to note that the coefficient of lift was assumed to be 1.3, an estimated maximum for the VR-15 airfoil with a high angle of attack without encountering stall. The free stream velocity was assumed to be the max tip speed of the blade plus the cruise speed of the vehicle. The two assumptions listed above provided a maximum amount of lift thought to be encountered by the blade.

| Lifting Force (L) | 109.02 N |
| Density ($\rho$) | 1.078 kg/m$^3$ |
| Free Stream Velocity (tip speed + vehicle speed) ($V_{fs}$) | 23.15 m/s |
| Planform Area of Blade (S) | 0.2903 m$^2$ |
| Blade Lift Coefficient ($C_L$) | 1.3 |

Table 4: Summary of Lift Calculations for Blade Displacement

Once the additional lift was calculated, the force was assumed to be a point force at 75% of the blade length. From here, it was easy to calculate the torque about the hinge and arrive at a final blade tip displacement of ± 1.7 ft, depending on whether the blade is advancing or retreating. Due to the size constraints of the HMMWV, it was not logical to have over three feet of rotor shaft between the two rotor disks. It was decided to implement a rotor shaft that could be extended to 3.5 ft when the vehicle is in operation and retracted to an adequate amount when the vehicle is in stowage. This will ensure the safety of the vehicle when in flight.

[Please note that the ± 1.7 ft also assumes a 'worst case' scenario. Friction was not accounted for in the hinge and the excess lifting force was assumed to be a point force at 75% of the span. Actual blade movement about the hinge is expected to be below 1.7 ft.]

To further eliminate the risk of contact between the blades, each rotor disk will be out of phase with the other disk by 90 degrees. When an aerodynamic force is placed on a rotor blade, the physical reaction to this force is not recognized until the disk has rotated 90

14

degrees (Berry 2002). When the disks are out of phase with each other by 90 degrees, the maximum displacement of the blade tips will occur when the blade is not directly over or under the coinciding blade on the other disk.

Once the basic design and placements of the rotor blades had been decided, it was necessary to resolve the method by which the motion of the vehicle will be controlled. Simply changing the pitch of the individual rotor blades as they rotate about the hub can control the total motion of the vehicle. Commands will be sent via the avionics to mechanisms in the rotor system, which will enable the vehicle to roll, yaw, and pitch. Traditional rotorcraft use control devices located at the hub of the rotor system that physically change the pitch of the individual rotor blades. This takes a great deal of force and often requires the use of a hydraulic system, which adds much unwanted weight.

The design of the Choctaw is very innovative in this sense. Instead of using control, or feathering, devices at the hub, servo-flaps will be placed on each blade at a point that is 75% it's total length. A servo-flap is much like an elevator on a fixed wing aircraft. A small electric motor changes the pitch of the flap and causes the entire blade to pitch up or down. The aerodynamic forces that are acting on the blade cause the pitching in the actual blade. Simply utilizing the aerodynamic forces already present on the rotor disk through the servo-flaps eliminates the need for a heavy, complex hydraulic system.

The servo-flaps do add little in the way of extra weight at around 6 lbs each, and use only a fraction of the total electric power required by the vehicle. Another advantage of the servo-flap is that the vibration in the blades is actually reduced--the reason being again that the only forces acting on the blades are aerodynamic rather than mechanical force from the hub.

In the following figure, Figure 9, the reader can see the servo-flaps used on this Kaman rotorcraft (http://www.helis.com/howflies/servo.htm). Notice the aileron-like flaps toward the end of the span of the blade.
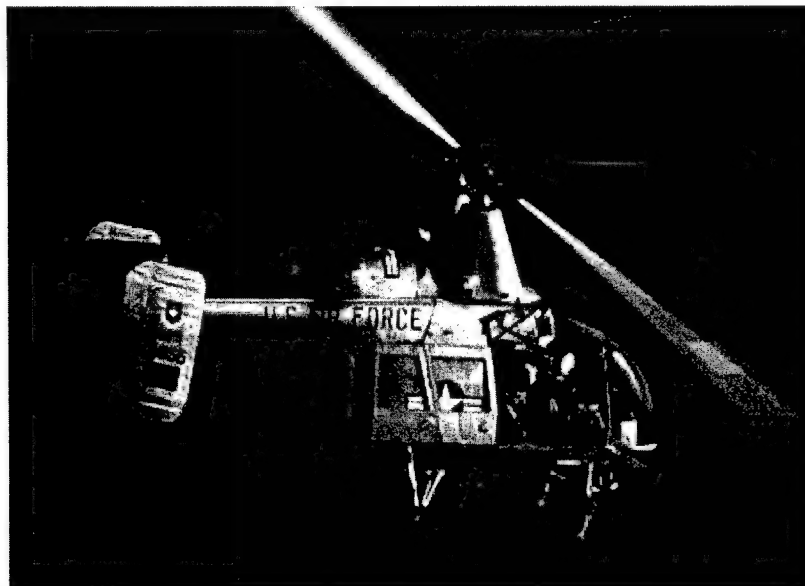


Figure 9: Servo-Flaps in Use on Kaman Rotorcraft

The last aspect of the rotor system design is the implementation of auto-folding blades. In this design, one blade on each rotor disk will be spring loaded at the hub. When the vehicle is in ground operation, the spring-loaded blade will fold and align with its counterpart on the opposite side of the rotor shaft. When the vehicle is in forward flight, angular momentum will hold the spring-loaded blade in tension and allow the blade to re-align itself in the correct position. This design will be of particular advantage in ground operation.

The end result of the design of the rotor system make it a lightweight, agile vehicle. The enhancements shown in this section not only increase the performance ability of the vehicle, but also increase the durability. This is something that J5 Engineering believes is pivotal in the present day combat environment.

## 2.3 Propulsion and Power

Two concepts were considered at length for use in the Choctaw. One system used two Internal Combustion Engines (ICE) to provide power to the rotors as well as to turn an alternator in order to provide electricity for ground power and avionics. This configuration fits to the CDD and is presented in the Appendix C2. The other system used an ICE for air propulsion and a fuel cell system for ground and avionics power.

In selecting a hybrid ICE/fuel cell concept, the J5 Engineering team has accepted a certain amount of technological risk. However, J5 feels that the analysis shown below will convince that the benefits outweigh the risks.
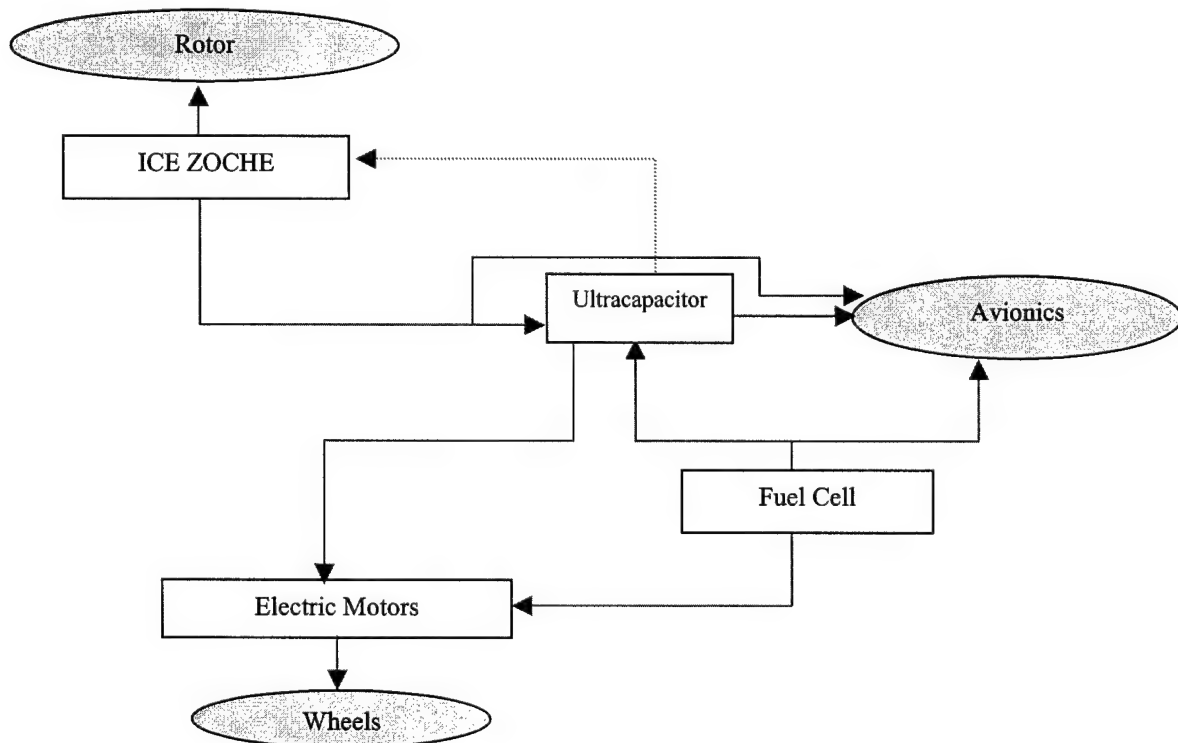


Figure 10: Overall Power Design Configuration

### 2.3.1 Air Power

This section describes the Choctaw's aerodynamics requirements. To offset frictional losses, a 10% factor was added to the power requirements.

*For a vehicle weight of 1100 lbs:*
Hover Power = 96.15 hp
Climb Power = 112.17 hp
Cruise Power = 60 hp at 76 ft/sec
10% more due to friction:
Hover Power = 105.77 hp
Climb Power = 123.38 hp
Cruise Power = 66 hp at 76 ft/sec

It is clear that the most important air power constraint is 124 hp. To properly size an air power plant, a worst-case power need of 150 hp is assumed in case an emergency situation required extra power. In choosing the engine, weight and noise emission were favored.

At first, J5 was very interested in the four-stroke engine SMA SR 305. This motor is very powerful, but at more than 360 pounds, it was considered far too heavy. Then we studied revolutionary engines like the Quasiturbine or the Dynacam engine; however, the concepts used by those technologies are not enough developed for the moment, as prototypes have not yet been manufactured. Auxiliary Power Units were considered, but they are too noisy.

The air engine chosen is manufactured by a German firm named Zoche Company. This engine is a two-stroke engine, radially arranged, with four pistons. One important problem with this kind of engine is the high power required to start the engine. To solve this problem, Zoche engine uses a patented air starter system that provides pressurized air to the engine to make it start.

Here are some characteristics of this engine:

| Type \| Designation | ZO 01A | |
|---|---|---|
| Power | 150hp=110kW | |
| Size | 555mm*648mm*725mm | |
| Weight | 84kg=185lbs | |
| Fuel | Diesel, JP4, JP8 | |
| Specific Fuel Consumption | Max power | 0.365lb/hp.hr = 225g/kWh |
| | Cruise | 0.346lb/hp.hr = 212g/kWh |

### 2.3.2    Ground Power

### 2.3.2.1 Electric Engines

Electric engines are attractive because they present several advantages such as small physical dimensions, maintainability, and low noise emission. These engines require an electric power source. Both configurations should be powered by electric motors for the ground propulsion. The Choctaw uses four motors, one for each wheel.

Brushless motors are highly efficient due to the use of thick conductors of low resistance and a closed coupling with a magnetic field. They can develop high power and torque at low speed resulting from high magnetic flux acting on both sides of the armature. In addition, the power to weight ratio is high due to high efficiency and an optimized disc shape. They are also highly reliable. The electronic control is simple, as speed is proportional to voltage. Braking and regenerative braking are possible. The weight of a brushless motor is about 8 kg for a power of about 2.5 kW.

### 2.3.2.2 Fuel Cells

The theory of fuel cell technology was elaborated in 1802, but fuel cells have only been developed for a few decades. Car manufacturers are now very confident in this technology, and are currently funding many researchers in order to install fuel cells in their vehicles as soon as possible. But fuel cells have shown their efficiency in many NASA programs, such as NASA's Space Transportation System (STS) where they have provided electrical power. Fuel cells seem to be the future of electric supplies. This technology is skyrocketing, especially in transportation applications. They are a promising long-term technology that allows flexibility to the mission.

Unlike batteries, fuel cells are almost endlessly rechargeable: only fuel is needed. Some of the other pros and cons are summarized in Table 5:

Table 5: Pros and Cons of Fuel Cell Technology

| Pros | Cons |
|---|---|
| 40% < yield < 50%<br>High power density<br>Noiseless<br>No moving parts<br>Maintainability<br>Reliability<br>Environmental friendly | Use of Hydrogen<br>Hydrogen supply on the battlefield |

The fuel cell is sized to provide average power to electric motors, avionics, and ultracapacitor. This one will deal with peaks of power.

Given the rate of technological advancement in fuel cells, we anticipate a fuel cell system of the following characteristics to be available in 2012:

| | |
|---|---|
| Performance | 5.50kW for 2 hrs |
| Volume | 19L |
| Weight | 20.8kg=46lbs |
| Fuel | Hydrogen |
| Cost | 50$/kW => 275$ |

### 2.3.3 Transmission

### 2.3.3.1 Air Transmission

The aim of the transmission system is to transmit and distribute mechanical power. The design has been developed while keeping in mind reliability, maintainability, efficiency and weight. The air transmission system constitutes an important element in the UHV because it transmits the power coming from the air engine to both rotors. This system is sized in order to support the UHV's maximum lift forces during the climbing because it is the worst load case for this system. The rotor shaft speed is fixed at 830 rpm and the maximum Zoche engine shaft speed is fixed at 2500 rpm. The maximum power used for the transmission calculations is 150hp. The position of the Zoche Engine is supposed to be horizontal.

This system has to support the maximum constraints due to the maximum engine torque. The other parts, such as axis or bearings, have to support the UHV loads with a minimum deformation in order to run correctly. Conic gears as the other components will be sized according to the maximum constraints.

The system configuration is similar to the one above, but the planetary gear train and the distributor are removed. Another conic gear is inserted in the system. J5 sized a light, low noisy, simple and efficient device, in order to get the reliable transmission system possible.

### 2.3.3.1.1 Main Gear Box Characteristics
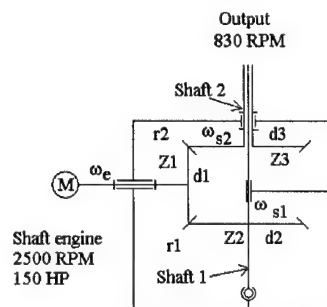


$Zn$ is the number of teeth of the conic gear n,
$r1$ and $r2$ are the reductions ratios,
$dn$ is the pitch diameter of the gear n,
$\omega e$ is the shaft speed input,
$\omega s1$ is the shaft speed output for the rotor 1,
$\omega s2$ is the shaft speed output for the rotor 2.

Figure 11: Gear Box Diagram

The type of gears chosen is spiro-conic concurrent. These gears decrease the noise of the system and present a good mechanical resistance.

The gear specifications are as follows:

| Pitch Diameter | D1 = 180 mm, D2 = D3= 58.065 mm |
| Teeth Number | N1 = 10, N2 = N3 = 32 |
| Pressure Angle | 20° |
| Average Spiral Angle | 35° |
| Quality of Manufacturing | 6/7 (DIM norm) |
| Materials | 18 NC 13 |

Shaft diameters are sized in order to avoid flexion and compression constraints that would create deformations. These are harmless to the functioning of the system. Thus, the shaft engine has a diameter of 40 mm; shaft #1, is 65 mm diameter; and shaft #2 has an outside diameter of 100 mm and an inside diameter of 75 mm.

### 2.3.3.3.2    Bearings

Bearings drive the different axes with the minimum friction possible. They also have to support axial and radial loads. The main rule of the bearing design consists of using one bearing fixed on each shaft with the other one free. This rule is due to manufacturing constraints. For the shaft engine, a two-ball-row bearing should be used because it will be able to support important axial and radial loads during high speeds.

For shaft 1, because they support very important axial loads, two roller bearings will be used; the first one at the base of the shaft and the other one opposite with the first one.

For shaft 2, only one bearing is designed, but on the plane another one will be just outside the shaft. They will have the same characteristics as the shaft ones. The dimensions are different.

### 2.3.3.3.3    Miscellaneous

In order to correctly set the gears on the shafts, sprockets have been sized to resist the maximum power defined above.  Other parts have been studied to reduce to the minimum power while maintaining a high load resistance.  Flow oils should be studied to optimize the lubrication. EP 80 oil is bubbled through the transmission.

The set up of the transmission box on the UHV structure can be realized using three joints (not shown on the CATIA drawing).
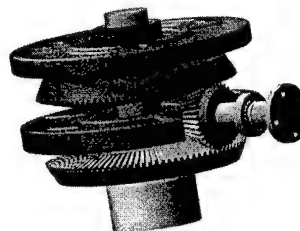


Figure 12: Air Transmission System Concept

Here are the specifications of the bearings:

| Diameter | 360 mm = 14.17 in |
|---|---|
| Witdh | 329.21 mm = 12.96 in |
| Total Weight | 35kg |

This gearbox will meet the UHV requirements. It should be reliable, light, quiet, and easy to maintain.

### 2.3.3.2        Ground Transmission

### 2.3.3.2.1        Ultracapacitor

Capacitors are a 100-year-old technology; however, ultracapacitors are a new energy storage technology ideally suited for applications needing repeated bursts of power (for fractions of a second to several minutes). The US Army has already developed its own ultracapacitors.

To make power available when needed by the application, the ultracapacitor charges itself from the fuel cell. This power is then discharged from the ultracapacitor at rates demanded by the application. The ultracapacitor can be repeatedly charged and discharged at rates optimized for the application which allows the entire system to be tailored to optimally meet both power and energy requirements.

Capacitors are superior to batteries with respect to energy density, longevity, and performance. Moreover, integration of ultracapacitors into the UHV allows for a slower transient response from the fuel cell and thus, a fuel economy. Furthermore, ultracapacitors can be a lifetime subsystem by withstanding wide temperature ranges, requiring little maintenance, and can be placed more optimally for vehicle ergonomics.

Two PC2500 are used in series. The worst case concerning peak power was used: the ground system. This solution also allows us to get a good redundancy for the starting of the engine. In fact, to start the engine, both ultracapacitors will be used. Each will be charged before the mission with the help of the ground station.

Here are the main characteristics of the ultracapacitor:

| Manufacturer. | Maxwell |
|---|---|
| Name | PC2500 |
| Capacitance | 2500 F |
| Rated Current | 625 A |
| Size | 161mm*61.5mm*61.5mm |
| Weight (1) | 0.725kg=1.60lbs |
| Operating Temperatures | -40°C--70°C |

### 2.3.3.2.2        Heat Transmission

Considering the current used, the diameter of the electric lines were also evaluated. Usually a 10A current corresponds to a 1 mm² section. Thus the most important diameter will be 9mm. This is a reasonable value and of course, it can be reduced by using a better heat exchanger,.

### 2.3.4   Conclusion

Fuel cells are useful technologies for this UHV due to its inherent-to-the-technology pros, including high power density, reliability, noiselessness, absence of moving parts, and its promising long-term capabilities.

From a mission point of view, fuel cell allows flexibility: room is gained for the payload, or fuel in order to increase the duration of the ground phase or the performance of the UHV.

The disadvantage of this system remains the fuel used.  However, it does not represent any safety problems as leak-before-burst tanks that can withstand small-arms fire are used to contain the hydrogen.  Also, reliable hydrogen production could be logistically feasible on the battlefield by the time the Choctaw takes flight.

Table 3: Weight Statement for Power Plant

| ICE Zoche | Dry Weight | 184.8 lbs | 84 kg |
|-----------|------------|-----------|-------|
|           | Oil | 17.6 lbs | 8 kg |
| Fuel Cells | Total Weight | 45.8 lbs | 20.8 kg |
| Transmission | Weight | 77 lbs | 35 kg |
| Electric Motors (4) | Weight | 52.8 lbs | 24 kg |
| Ultracapacitor (2) | Weight | 3.3 lbs | 1.5 kg |
| TOTAL WEIGHT | | 381 lbs | 173.4 kg |
| 34.65% of 1100 lbs | | | |

## 2.4 Ground Robotics/Vehicle

### 2.4.1   Introduction

The ground robotics system features four 9-inch wheels that are electrically driven and have a spring suspension. Types of alternative ground systems considered during the design process included wheels, tracks, skids, and even hovercraft.  While track systems are better for crossing a wide variety of terrain, they tend to have a relatively high weight cost.  Tracks are considered in combination with tracks, like a snowmobile, and also alone as used by helicopters.   While tracks may be excellent for snow and soft conditions, the UHV is required to travel at least half a kilometer.  Skids do not offer ground mobility and are relatively heavy in combination with tracks.  Hovercraft technology looked attractive for a while, especially since the equipment for flight may have also been used for hovercraft propulsion on the ground.  Unfortunately, hovercraft steering is relatively slow to respond and would require additional avionics and a constant level of propulsion to maintain the UHV's position on a slope.

### 2.4.2   Selected Design

The selected design uses a compact, simple solution to the mobility and operational needs of the UHV.  Worst-case scenario requirements were derived from the CDD to begin analyzing

the operational needs of the vehicle. Those requirements include 12 km/hr ground speed, a 12 degree climb slope for the path of the vehicle, a maximum vehicle weight of 1500 lbs, a single kilometer ground radius, over an operational time period of at least two (2) hours. When calculating the power requirements, it was necessary to execute all operations using less than 90% of the system's maximum rated power.

Based on the vehicle's design for flight, ground velocity, and maximum rate of climb, drag and physical obstructions in the road that would slow down forward travel were not significant enough for the focus of the power requirement analysis. Instead, the design-inherent power requirements were most significant: skid steering and mounting the electric motor in the wheel presented the greatest design challenges.

Skid steering is simply accomplished by fixing the orientation of the wheels and alternating the rotation characteristics of each wheel independently to rotate the vehicle. This design is based on the operation of Bobcat company skid-steer loaders (http://www.bobcat.com/). To execute a right-hand turn, this design depends on the avionics system to command the tires on the left side of the vehicle to turn in the forward direction while the tires on the right side of the vehicle turn in the backward direction, all at the same time, to spin the entire vehicle so that it faces right. One advantage of this type of steering is that it has a "zero turning radius" because when executed uniformly, the vehicle can spin over one point, which would be good when the vehicle must land in tight spaces (http://www.howstuffworks.com/skid-steer1.htm).

The electric motor was selected based on the power requirements. Because of the uncertainty involved in executing a skid-steering turn, a safety factor of 2.0 was used to size the motors. A 3-hp electric motor was selected for each wheel such that the diameter of the electric motor would be small enough that the electric motor might fit into the hub of the wheel with enough clearance for the hub of the wheel to spin freely around the edges of the electric motor. The wheels selected featured a hub whose depth into one side permitted three (3) inches of penetration at a hub clearance diameter of 7.5 inches.

The electric motor featured a maximum diameter of seven (7) inches. The 0.25-inch clearance will be sufficient for this rigid design. The driveshaft of the electric motor will be bolted to the wheel hub. The ends of the shaft will fit into bearings allowing the driveshaft and wheel to spin together, freely. All other components of the ground robotics system are fixed.

The electric motor/wheel assembly, as seen in Figure 13 and Figure 14, is at the end of a shaft that looks much like the front wheel of a bicycle. The shaft extending from the vehicle will fork around the wheel. The driveshaft will interface with the drive shaft via bearings that support the weight of the vehicle while maintaining free wheel rotation. The driveshaft requires slotted shafts to fit over the shaft designed by the motor manufacturer in order to span the distance between each shaft of the fork.

The electric motor will be powered via wires that run along the shaft that the motor housing is mounted to. Fixing the motor housing allows the motor to exert force on the driveshaft relative to the vehicle frame, powering the wheel's motion.
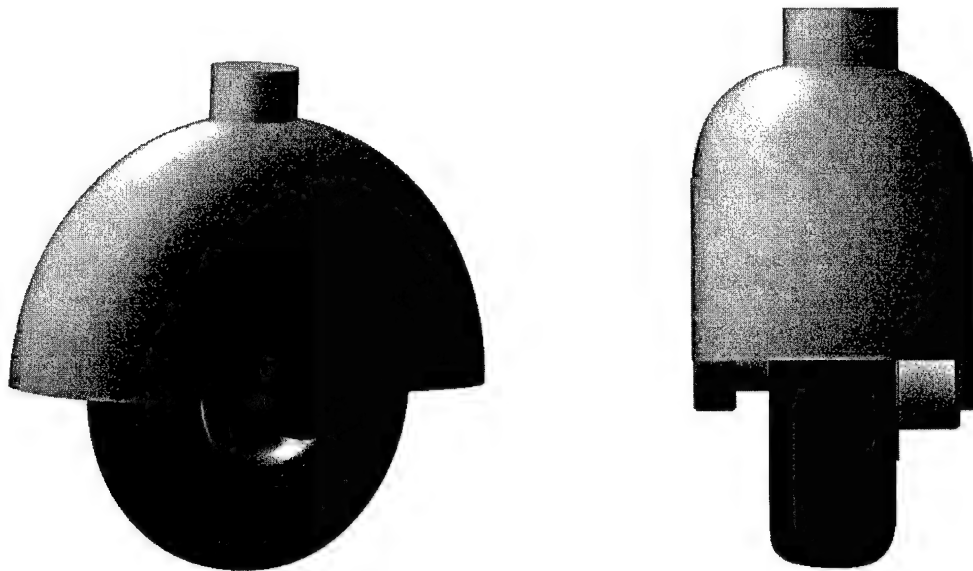


Figure 13: Three-Dimension Rendering of Wheel Assembly
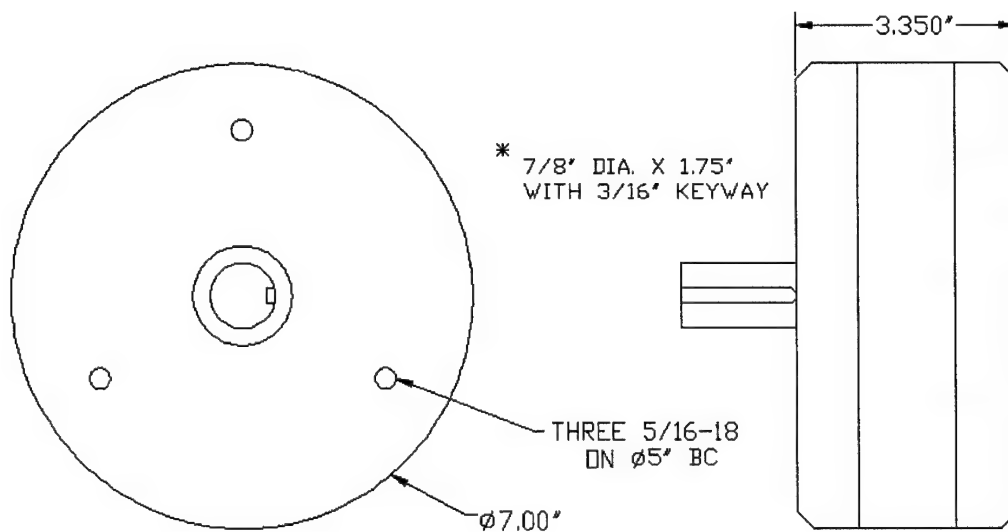


Figure 14: CAD Drawing of Wheel Tolerances

Worst-case mobility requirements incorporated possible failure modes, operational conditions, and critical events during the execution of a mission. To address contamination

of the electric motor by dirt, water and other substances, it will be fully enclosed and air will be forced through the shaft much like air vents in the side door of passenger vehicles. To address high-impact landings from flight, stiff springs bearing loads of up to 3000 lbs will be installed above the wheel faring to allow up to six (6) inches of spring compression in the event of a hard landing. Current options being explored are run-flat tires and a tire pressure-relief system for improving traction in the wheels over soft surfaces such as sand and mud.

## 2.5 Mechanical Configuration/ Structures

### 2.5.1    Materials

The Choctaw is designed for durability and maintainability. Materials that possess high mechanical properties as well as high fatigue resistance are used in its construction. Also, weight plays a very important role in the construction scenario, and this needs to be factored into the selection of materials. Material selection was partly based on the environment where Choctaw operates.

The frame is constructed of Titanium IMI 834 (Netcomposites 2001) having density of 0.164 lb/in$^3$ and modulus of elasticity of 17400 ksi. The fatigue and ultimate tensile strength are 76.9 ksi and 152 ksi, respectively. The core material is Nomex honeycomb with density of 0.000686 lb/in$^3$ and shear modulus of 4.06 ksi combined with epoxy resin. A 0.25-in Nomex honeycomb core combined with epoxy resin gives excellent mechanical properties and low density. Epoxy resin holds high mechanical properties as well as high fatigue resistance. It also has high water resistance. One of the disadvantages of epoxies is critical mixing and corrosive handling. One of the important things when choosing an epoxy resin was its toughness.

The skin of the Choctaw is constructed using Aramid Fiber/Epoxy combination. Due to the operation environment, impact resistance was considered. Aramid fibers are used extensively in ballistic applications having high tensile strength 450 ksi, elastic modulus of 19000 ksi and low density .052 lb/in^3 giving very high specific strength. The rotor blades are constructed using carbon fiber/epoxy advanced composite having a density of .0614 lb/in^3 and ultimate tensile strength of 129 ksi.

Table 4: Materials Summary for the Choctaw

| Component | Material | Information |
|---|---|---|
| Frame | Titanium IMI 834 | High strength to weight ratio |
| Core | Nomex honeycomb/Epoxy resin | Good mechanical properties/fatigue |
| Skin | Aramid fiber/Epoxy | Good impact resistance |
| Blades | Carbon Fiber Composite | Very light weight |

## 2.5.2 Construction

The Choctaw is constructed using prepreg molding. In prepreg molding, the core material is pre-impregnated by the manufacturer under heat and pressure with pre-catalyst resin. The prepregs are laid on top of the mould surface and heated to 120-180 °C. The prepreg molding takes place in a pressurized oven. This construction technique fits well with the selected materials. Material options include epoxy resins and any type of core materials.

Some advantages for this technique are good health and safety characteristics and resin content in the core can be accurately set which could affect mechanical properties. Disadvantages are that the tooling needs to be able to handle process temperatures and core material has to withstand process temperature and pressure.

Please refer to Figure 15 for a likely construction scenario.
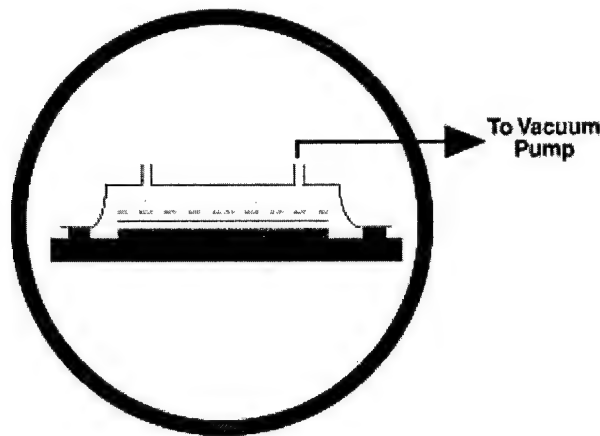


Figure 15: Choctaw Construction Scenario

As mentioned earlier, vehicle maintainability is important. A portable repair system also known as "Hot Bonder" is especially useful for field repairs in situations where it is hard or impossible to remove a damaged part. Such a portable repair system is often used to control heat air guns and heat blankets. It requires an electrical power source and some require a compressed air source. Refer to Figure 16 below for a visual of this system.
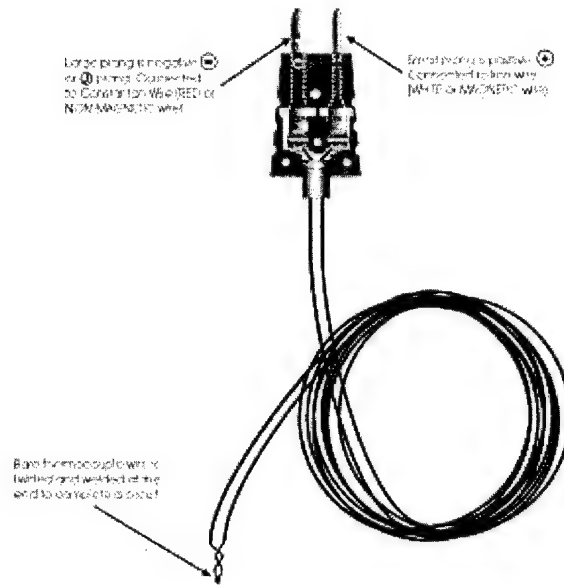
Figure 16: Hot Bender Portable Repair System

## 2.5.3 Mass Properties

The Choctaw is designed to have a good strength-to-weight ratio. Each component was selected to gain maximum performance during the mission profile. Table 5 shows the weight of individual components and subsystems. The repair kit, extra tires and fuel are also included in the final weight estimate.

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Table 5: Choctaw Weight Breakdown

| UHV | Weight (lbs) |
|---|---|
| **1. Air drive system:** | |
| o  Engine/motor | 202.40 |
| o  Transmission | 77 |
| o  Rotors | 52.14 |
| o  Hub | 25 |
| -  **Subtotal** | 356.54 |
| **2. Ground Drive system** | |
| o  Fuel cells | 45.8 |
| o  Motors | 52.8 |
| o  Mode (treads/wheels), | 71.94 |
| o  Other | |
| -  **Subtotal** | 170.54 |
| **3. Avionics and Sensor weight** | |
| o  Avionics | 30 |
| o  Sensors | 36 |
| o  Power sources | 3.3 |
| o  Biological warfare | 55 |
| -  **Subtotal** | 124.30 |
| **4. Structural Weight** | |
| o  Frame | 20 |
| o  Skin | 30 |
| o  Core | 100 |
| -  **Subtotal** | 150 |
| **5. UHV Subtotal** | 801.38 |
| o  Weight Contingency (20%) | 160.28 |
| **UHV DRY WEIGHT** | **961.66** |
| **6. Mission-Dependent Weights (max)** | |
| o  Max Payload Weight | 60 |
| o  Max Optional Sensors | 55 |
| o  Max Fuel Load | |
| -  **Subtotal** | 115 |
| **UHV MAX GROSS TAKEOFF WEIGHT** | 1076.66 |
| **7.  Support and Handling Equipment** | |
| o  Ground Station | 20 |
| o  Shipping Container/ Palate/straps | 100 |
| o  Test and Measurement Equipment | 15 |
| o  Spare Parts /Tools  (up to four missions) | 100 |
| o  Additional Mission-Dependent Sensors | 20 |
| -  **Subtotal** | 245 |
| **UHV SYSTEM SHIPPING WEIGHT** | **1321.66** |
| | |

Figure 17: Subsystem Weight Breakdown, Pie Chart



]
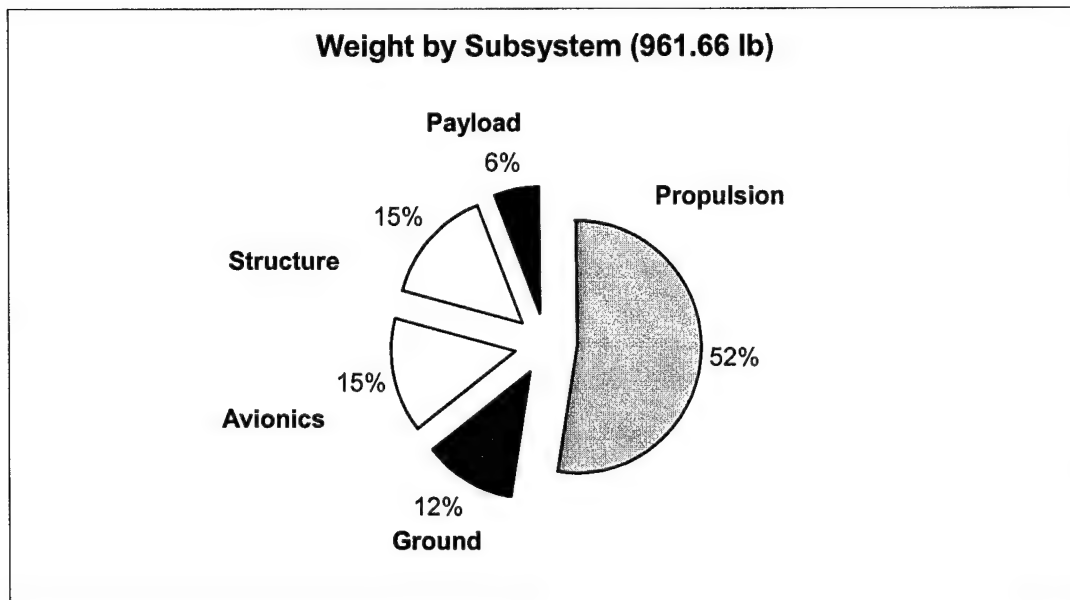
## 2.5.4 Vehicle Configuration

The Choctaw's fuselage is shaped like a pistachio nut. It is round in the longitudinal direction and the front and back of the vehicle taper toward the center, forming a streamlined shape. The overall length is 84 in., and the overall width is 45 in. The payload is located in the center of the vehicle toward the bottom. A weight balance was calculated for the Choctaw after all the weights of the components and their dimensions were found. The weight balance was made from the horizontal side view. This was important because of stability in the air. If the center of gravity were too far back, the Choctaw would be unstable and could become inverted. The center of gravity (CG) was therefore placed just in front of the rotor. The CG is located 35.6 in. from the front of the vehicle.

Another weight balance was calculated from the vertical side view. This was done to make sure that the center of gravity is low enough so that the vehicle does not tip over when driving on a 12-degree slope. The vertical component of the CG is located 28.8 in from the ground level. The Choctaw also features removable panels that are inside the payload area, this allows easy access to change out the fuel cell or the ultracapacitors. The payload slides on tracks and is enclosed by a hinged panel. Sling attachment points are provided on the topside of the fuselage to allow for sling-transportation by a UH-60 Blackhawk helicopter.

The Choctaw incorporates a folding blade design where the blades are spring-loaded. As the rotational speed increases, the blades are forced to sling outward due to angular momentum. We calculated some rough estimates for centripetal force as the function of rotational speed for different rotor diameters. This force is critical when determining the pin size required at the end of the blade where it attaches to the hub. It was assumed in the calculations that blades had uniform geometry in the longitudinal direction and rectangular cross-section and

were hollow inside. Figure 18 shows the results of this calculation for various blade diameters.

**Centripetal Force vs. Rotational Speed**
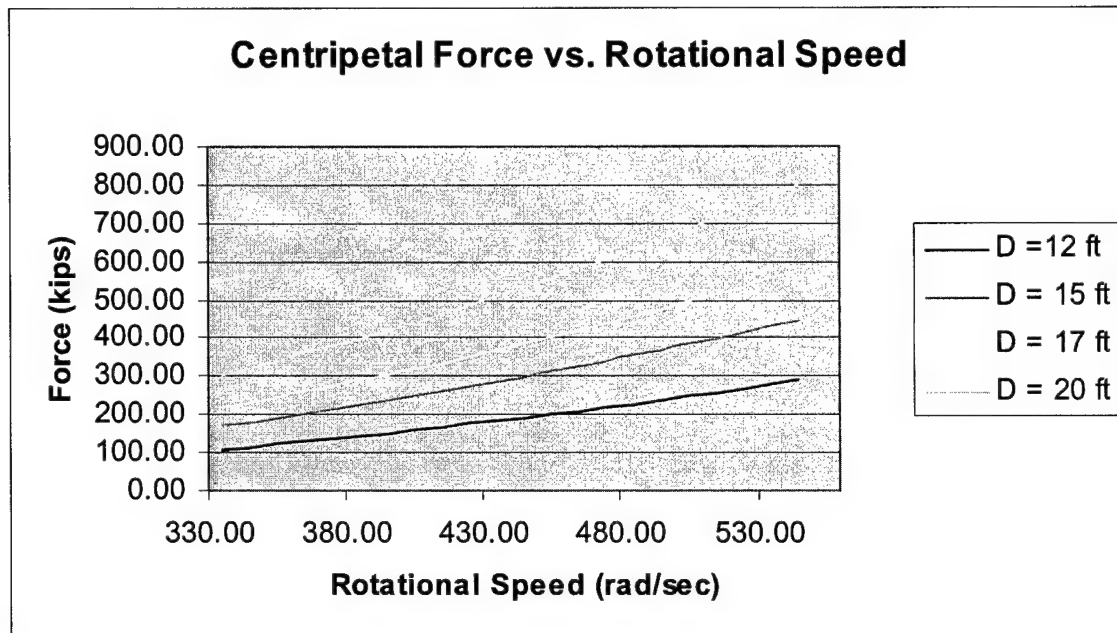


Figure 18: Centripetal Force on Blades vs. Rotation Speed of Blades

As one can see from the curve, the force increases as the diameter of the rotor increases. The Choctaw has a rotor diameter of 15 ft and a tip speed of 650 ft/sec; therefore, the force exerted by the blade is approximately 430kips. From this, the pin diameter was calculated to be 1.2 in. The centripetal force exerted by the blade to the hub was calculated using Equation 3.

$$F = \int_0^r \rho \cdot (B \cdot H - b \cdot h) \cdot \omega^2 \cdot r \, dr$$

Equation 3

## 2.6 Avionics/Flight Control

The UHV is designed to operate in both autonomous and semi-autonomous modes. Avionics and sensors provide important navigational and flight control capabilities. The avionic capabilities include: nap of the earth flight, terrain following, and terrain avoidance. The sensor capabilities include: chemical and biological threat detection, gathering information on threat activities, weather detection and visibility control, and friend or foe detection. Other capabilities of the UHV include: secure link data communications; and satellite communication for the differential GPS.

Table 6: Summary of Avionics and Sensor Packages

| Component | Manufacturer | Power (Watts) | Weight (lbs) | Dimensions H x D x W |
|---|---|---|---|---|
| Differential GPS | OmniSTAR USA, Inc | 5 | 2.1 | 8.2x2.6x5.25 in |
| CPU's for Various Flight/Sensor Applications | Various | 400 | 23 | 7.65x22.3x11.2 in |
| Sat Com Antenna | | 4 | 6 | 3x5x7 in |
| FLIR/Camera/Radar/IFF Sensors | Lockheed Martin | | | |
| Biological and chemical sensors (FLAPS) | unknown | 320 | 50 | 1.9cf |
| Weather Sensors | | | | |
| DRD11A Rain Detector | VAISALA | 2.3 | 500g | 110x80x175 mm |

## 2.6.1 Avionics

### 2.6.1.1 Components

One of the main components that allow semi-autonomous to autonomous flight is the Differential Global Positioning System (DGPS). DGPS is small and lightweight. It is a combination of a 12-channel GPS and L-band OmniSTAR differential receiver. The DGPS data allows the AI to make choices based on where it is, where it wants to go, and what actions need to occur to accomplish the current task, whether in flight or on the ground. The DGPS features sub-meter performance almost anywhere in the world. It has an antenna for communications and can be interfaced through cable for data input to navigational systems.

The central processing units (CPU's) needed for flight control, including the full authority digital engine control (FADEC), video and synthetic aperture radar (SAR) processing and secure communications, are all in one location. The fifteen-slot housing for these various processors provides protection and multiple input/output ports for connection with other units. The CPU's intake data from the sensors and/or the ground control unit (GCU) for stabilization during flight, tracking of air speed, and rotor controls. The FADEC interfaces with the engine, providing it with the correct fuel, air and ignition ratios required for optimum performance with minimum fuel expenditure. In the event of a malfunction or total failure of any system component, including the main control unit, a redundant system will automatically engage for uninterrupted operation of the aircraft. The inertial measurement unit within this unit also assists in attitude and heading information. (http://www.rotorway.com/fadec.html)

### 2.6.1.2 Communications

The communications of the UAV is by satellite communications (SATCOM) links that use secures wireless Ethernet Wavelan technology for remote and BLOS controls. The commander's GCU includes controls for landing, take-off, and in-flight commands as well as a flat screen display for video, radar, and nighttime IR sensor images.

## 2.6.2 Sensor Components

The UHV uses various sensors to send information to the control system to achieve the autonomous and semi-autonomous modes. The Fluorescent Aerodynamic Particle Sizer (FLAPS) system is used to gather information on Chemical and Biological threats. The FLAPS contains a detector/trigger function, sample collection function, and meteorological instrumentation. It also uses time-of-flight particle sizing, light scattering, and UV fluorescence intensity to nonspecifically detect biological and chemical agents in air samples.

The target sight system is the FLIR/Camera/Radar/IFF sensor. This sensor provides visibility, object detection, radar images, and full motion video. This is a color camera, an aperture TV camera, a variable aperture infrared camera (for light/night), synthetic aperture radar (SAR) for looking through smoke, clouds, or haze, and a Friend or Foe system for object detection. The camera produces full motion video and the SAR still frame radar images. To gather information on threat activities, the friend and foe sensor is use to identify objects by signal or shape. Once an object is seen, the sensor will send a signal to the control system telling it if the object is has detected is an enemy or a friend. (http://www.missilesandfirecontrol.com/our_news/factsheets/factsheet-HAWKEYE_XR_TSS.pdf)

The Wescam Suite and the Vaisala DRD11A Rain Detector sensor is capable of detecting weather activities. The SAR in the Wescam Suit detects the smoke, clouds, or haze in the atmosphere while the Vaisala DRD11A detects precipitation, rain intensity, and wind changes. (www.viasala.com)

Figure 19 shows a mockup of what the targeting system on the Choctaw might look like.
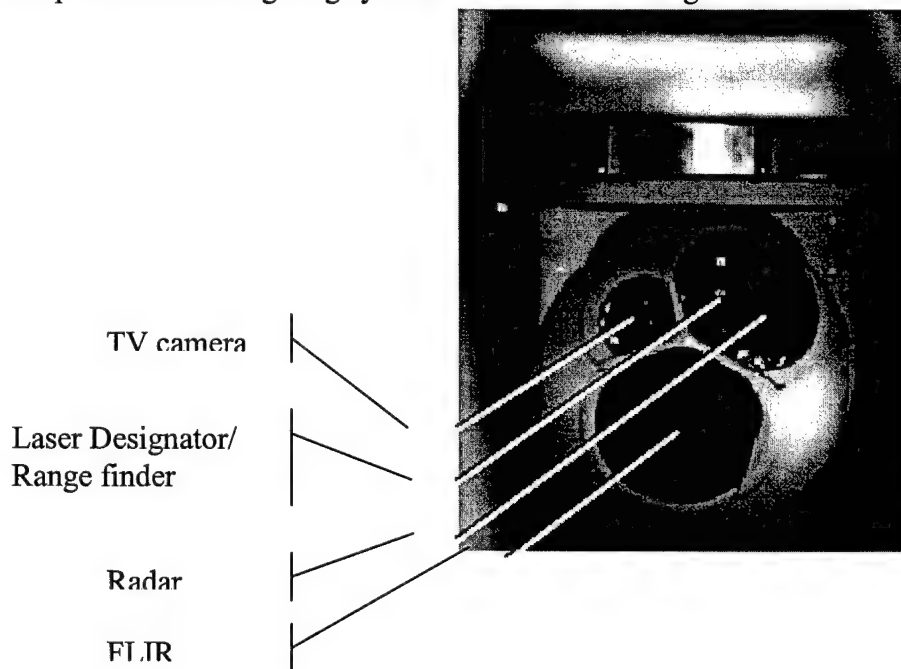


Figure 19: Mockup of Targeting System for Choctaw

## 2.7 Mission Simulation

This section summarizes the mission simulation of the UHV design verifying compliance with the Concept Description Document (CDD). Based on the mission profiles, the UHV design meets the requirements listed in the CDD. Table 9 and Table 10, both found in Appendix C, illustrate the mission profile calculations of the baseline operating and worst-case operating conditions using a spreadsheet code. Table 7 summarizes the requirements and results of the code for each profile.

Table 7: Summary of Requirements and Mission Profile Results

| Operation | Design Requirements | Baseline Operating Results | Worst Case Operating Results |
|---|---|---|---|
| VROC | 200-500 ft/min | 200 ft/min | 200 ft/min |
| Cruise Speed | 30-100 km/hr | 32 km/hr | 32 km/hr |
| NOE | 250-500 ft | 500 ft | 500 ft |
| Ground Speed | 6-12 km/hr | 6 km/hr | |
| Fuel Type | Diesel or Jet | Diesel | Diesel |
| FCR | N/A | 10 gal | 18 gal |
| Capacity w/Reserve | 10 % | 11 gal | 20 gal |

Mission Simulation reviewed two cases verifying compliance of the CDD. The cases investigated are baseline and worst case. Baseline profile is the normal operation and worst-case is engine operating at 100% in all segments with the exception of warm-up at being and segment 8 after electrical powered ground maneuvers.

The mission profiles consist of thirteen segments. Figure 20 illustrates and describes each segment from Segment 1 (engine start) through Segment 13 (hover and land).

**Critical Flight Conditions**
Altitude - 4000 ft. (Starting)
Temperature – 95 °F
VROC – 200 FPM

**Segment 4**
Cruise Outbound ALT
NOE 500 ft
Velocity 32 km/hr
Range 15 km

**Segment 10**
Climb to Combat
Operational
Altitude VROC
200 FPM

**Segment 11**
Cruise Inbound
ALT NOE 500 ft
Velocity 32 km/hr
Range 15 km

**Segment 1**
Engine Start Warm Up

**Segment 3**
Climb to Combat Operational Altitude VROC 200 FPM

**Segment 5**
Descend

**Segment 7**
Ground

**Segment 9**
Hover

**Segment 12**
Descend

**Segment 2**
Hover

**Segment 6**
Hover & Land

**Segment 8**
Engine Start Warm Up

**Segment 13**
Hover & Land
10% Fuel Reserve

Figure 20: Baseline Mission Profile

In determining each mission profile, the analysis assumed the vehicle and payload weight are 1100 pounds. The maximum power of the engine is 150 horsepower. Table 8 illustrates the engine function through the segments, identifying horsepower requirements and power usage in percent relative to maximum available horsepower. Losses due to friction are included in the data in Table 8 as well.

Table 8: Engine Function Ratings

| Function | Required Horsepower (hp) | Usage Percent (%) |
|---|---|---|
| Climbing | 125 | 83.33 |
| Cruise | 70 | 46.76 |
| Descending | 65 | 43.00 |
| Hovering | 110 | 73.33 |
| Idle | 10.5hp@750rpm | 7.00 |

The approach in verifying compliance was to use a code that determined fuel consumption of the engine at required vehicle operating condition. The code incorporated time, distance, airspeed, power requirements, and fuel consumption rate at each segment of the baseline mission profile.

The baseline mission profile use various fuel consumption rates based on the power requirements at specified segment. The worst-case profile used a constant fuel consumption rate operating the engine at 100% with the exception at engine warm-up at Segments 1 and 8. The power requirement used 7% rated power.

In summary, the mission profiled used engine power data to verify compliance with the concept description. The engine data was used in determining fuel usage and reserve amounts to accomplish the UHV design requirements of VROC, cruise speed, NOE, and ground speed.

Finally, all design requirements were met and fuel requirements were determined for baseline and worst-case mission profiles.

## 2.8 Blade Technologies

The Choctaw concept UHV designed by J5 Engineering has two significant blade technologies that provide added value to the customer. The first is the auto-folding technique discussed in Section 2.5.4, with Figure 18 on page 30 showing a family of curves depending on the rotational speed and blade diameter. This set of curves will be used to find a torsional spring to be placed at the base of the blades to bring them to a common resting place.

The second blade technology used in the Choctaw is the servo-flap concept discussed in Section 2.2. Figure 9 shows servo-flaps in use on the Kaman rotorcraft. The servo-flap technology removes traditional cyclic controls from a helicopter and greatly reduces the strain on the avionics to provide optimum flight characteristics for the UHV. The use of

servo-flaps also greatly reduces the weight of the rotors, providing more weight allowance for other necessary subsystems.

## 2.9 Electric Power Generation

Electric power generation for most aircraft is traditionally done with a two-component approach: batteries store an electromotive force (EMF) that can be used during times of peak electrical power need, and an alternator that is turned by an internal combustion engine provides voltage and current sized to an average power need.

In an effort to provide a unique design that will provide benefit to the customer, J5 Engineering staffers developed an alternative electrical power generation system that should perform similarly well while providing many added benefits. A fuel cell will be used to replace the alternator in terms of providing average power. The Choctaw UHV will have a tank of hydrogen on board to be mixed with atmospheric oxygen to produce electrical power on an average need basis. The fuel cell has been sized to meet the power needs during the ground phase of the mission, as the combination of ground maneuverability and the need for avionics and sensors to be active during the ground phase means that this is the highest point for average power consumption during the mission profile.

To provide peak power, a set of two ultracapacitors will be used as peak EMF sources for ignition, emergency power, etc. Much as a battery can be recharged by an alternator in a traditional electrical power generation approach, the ultracapacitors can be charged by the fuel cell during times of lower electrical power consumption.

The benefits of this alternative approach are many. This system replaces heavy batteries and alternators, giving a weight savings to the vehicle. Use of an alternator implies turning an internal combustion engine, which is undesirable for the ground portion of the mission, as stealth is the word of the day while on the ground. The fuel cell will operate in a near-silent mode with a much smaller acoustic and thermal signature than a traditional electric power approach would have. Finally, the ultracapacitors themselves will be a much smaller and lighter alternative to traditionally heavy batteries.

A schematic of the overall power generation scheme for the Choctaw UHV may be found in Figure 10.

## 2.10 Technical Summary
The Choctaw consists of several different components. It uses folding co-axial blades (airfoil being the Boeing Vertol VR-15). The hybrid propulsion system consists of an ICE engine (using the Zoche Z0 01A yielding 150 hp), fuel cells, and an ultracapacitor (using the Maxwell PC2500). Four electrically motorized wheels are used to operate the ground system using power generated from the fuel cells or ultracapacitor. FLAPS sensors are utilized to detect chemical and biological weapons. Ethernet Wavelan is used for BLOS while DGPS is for navigation and flight control. The performance of this vehicle is the following. The hover power is 105.77 hp while the cruise power is 66 hp. Access to a payload of a minimum 60 lbs (with a volume of 2ft x 2ft x 2ft) is through rolling doors without interface between the vehicle and payload. In order to maximize survivability, the Choctaw is shaped much like a

pistachio nut to diffract radar and deflect incoming rounds. Figure 21 shows a cross-sectional cut of the Choctaw UHV.
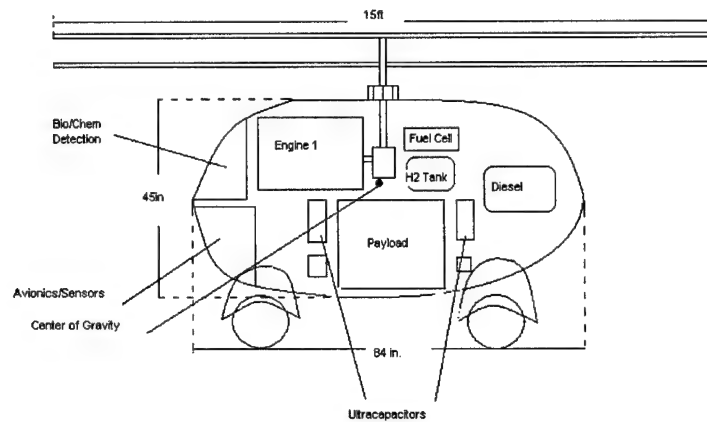


Figure 21- Cross Sectional Drawing

Table 9  Concepts Technical Information

| Comparison Criteria | Choctaw |
|---|---|
| **Overall Specifications** | |
| Air Configuration | Co-axial blades |
| Ground Configuration | Wheels |
| Payload Mass (lbs) | 60 lb |
| Gross Takeoff Weight (lbs) | 1033.66 lb |
| Aero Propulsion Type | ICE |
| Energy Source for Air Transport | FC or Ultracapacitor |
| Ground Propulsion Type | 4 Electric Motors |
| Energy Source for Ground Transport | FC or Ultracapacitor |
| Hovering Power (hp) | 105.77 hp |
| Cruise Power (hp) | 66 hp |
| Basis of Autonomous Control | CPU |
| Primary BLOS Method | Ethernet Wavelan |
| Primary Navigation Method | DGPS |
| Primary Sensor Type | Wescam Suite |
| Chemical/Biological Sensor | FLAPS |
| Method of Sling Attachment | |
| Method of Deploying Payload at Range | Thru roll-up doors |
| Enabling Technology | FC Development |
| Overall Dimensions, Stored (ft x ft x ft) | 7ft x 3.5ft x 9ft |
| Specialized Technology 1 | Folding Blade |
| Specialized Technology 2 | Ultracapacitor (PC2500) |
| | |

# 3.0 Implementation Issues

Programmatics is responsible for developing a project plan and acquisition strategy for the entire life cycle of the program. This consists of creating a Program Work Breakdown Structure (WBS), estimating a life cycle schedule from concept to disposal, and estimating cost for the entire life cycle. Uncertainty and risks must also be considered when developing the project plan, as these will affect scheduling and cost. An Integrated Program Management Array will need to be developed, listing the component elements of the WBS, along with associated costs, scheduling, risks, and resources. (McInnis)

Constructing a schedule and cost estimate is typically viewed as a technical activity. However, developing a project plan for a complicated system is mostly an art, requiring lots of intuition, judgment, and guesswork. The project's success will be measured by how closely it meets the original project plan. Therefore, developing a realistic project plan, rather than bowing to pressure to create an unrealistic optimistic one is a crucial challenge. (Little)

## 3.1 Programmatics Ground Rules and Assumptions

In the past, Unmanned Aerial Vehicles (UAV's) have been developed for Department of Defense (DoD) use through (1) contractor initiatives, (2) defense acquisition (milestone) programs, and (3) Advanced Concept Technology Demonstrations (ACTD's). Due to the Initial Operational Capability (IOC) being scheduled for 2012, it will be necessary to use an accelerated acquisition program. This will allow for shorter timelines and lessened oversight requirements. The acquisition program put in to effect will be based on the New DoD 5000 Model, but will not be subjected to all statutory (i.e.. legislated) and regulatory (i.e.. imposed by DoD) requirements (USD & ASD Staff).

Operating and Support (O&S) costs typically constitute a major portion of a system's life cycle costs and, therefore, are critical to the evaluation of acquisition alternatives. (OSD) Using the Army's current Tactical Unmanned Aerial Vehicle (TUAV) or Shadow 200 as an example for distribution, the Unmanned Hybrid Vehicle (UHV) will be used to provide close range (i.e.. less than 50 km) reconnaissance, surveillance, and target acquisition to the ground maneuver brigade commander. One UHV "system" will consist of two ground control stations (GCS's), one portable ground control station, one portable ground data terminal, four remote video terminals (RVT's), and a minimum of three UHV's. To fully deploy one entire system will require at least four High Mobility Multipurpose Wheeled Vehicles (HMMWV's) and seventeen personnel. If maintenance is required, a fifth HMMWV and five additional personnel will be required. For full self-sustaining operational capability, it will be necessary to use at least three C-130's (TUAV).

Eventually, four systems will be delivered to each of the army's current ten divisions. Three will be deployed to the direct support (DS) companies and one to the general support (GS) companies of the Military Intelligence (MI) battalion. This will result in at least forty systems being deployed at peak operational capability (TUAV).

The customer has requested 300 total UHV's or units to be produced. Two additional units will be produced as prototypes. Approximately twenty-six percent of the 300 units will be classified as spares. The number of spares is based on historical attrition rates associated with past UAV programs. (Carmichael 1996) A portion of the spares may be stored in sealed containers for up to ten years and placed in strategic locations for use in rapid response situations. (USD & ASD Staff)

## 3.2 Work Breakdown Structure

A Program WBS was developed using the Department of Defense Handbook Work Breakdown Structure, (MIL-HDBK-881) as a guide. The primary challenge is to develop a Program WBS early in the conceptual stages of the program, which will evolve through iterative analysis as the program progresses. The success or failure of a project can be directly related to the development of the WBS. (McInnis) The WBS provides a framework that assists during the life of the program in the following ways:

- Separates a defense material item into its component parts, making the relationships of the parts clear and the relationships of the tasks to be completed to each other and to the end product clear.
- Significantly affects planning and the assignment of management and technical responsibilities.
- Assists in tracking the status of engineering efforts, resource allocations, cost estimates, expenditures, high risk areas, and technical performance.

The Program WBS encompasses the entire program and consists of at least three levels. Level 1 is the entire defense material item (i.e. the UHV). Level 2 lists the major elements of the defense material item, and Level 3 lists the elements subordinate to Level 2 major elements. The WBS needs only to list the top three levels unless items of high risk or cost are identified. It is the Program Manager's (PM's) responsibility to maintain the Program WBS as it evolves and to develop a WBS Dictionary that lists and defines the WBS elements. By the end of the development phase, the Program WBS should be fully defined to its lowest level (DoD Staff).

The Program WBS is located in Appendix A. The Program WBS is shown as both an outline and a wire diagram. Note that each product element in the WBS will have an associated corresponding Integrated Product Team (IPT). The IPT encompasses each of the life cycle processes (i.e.. development, manufacturing, testing / verification, deployment, operations, support, training, and disposal) (Gunther).

## 3.3 Life Cycle Schedule

The projected life cycle for this program began with concept exploration in Fiscal Year (FY) 2002 at the University of Alabama in Huntsville (UAH) and is projected to continue until disposal sometime in FY2030. This timeline was determined by establishing IOC to occur during FY2012, as stated in the Concept Description Document (CDD), and assuming a program life expectancy of approximately twenty years as is customary for Army programs. (OSD) Figure 22 shows the O&S phase of a typical twenty-year life expectancy. The total

number of units to be produced and fielded has been distributed over the twenty-year period from FY2010 to FY2030. This will allow for improvements to be made as new technology develops and problems with the final design become apparent after the first units have been deployed. This will also allow for the program to be cancelled ahead of the scheduled disposal date if problems with fielded units cannot be remedied.

Figure 22: System Life Expectancy O&S Phases (OSD)

The program schedule can be seen in Appendix B. Phase 0(concept exploration) began in FY2002 and will continue until the Milestone Decision Authority (MDA) has reviewed the project and determined that Milestone A (MS A) has been reached. This should occur in FY2003, and Phase I (concept and technical development) will begin. Phase I will continue until the MDA reviews the project and has determined that MS B has been reached. This should occur in FY2007 and Phase II (system development and demonstration) will begin at this time. Two prototype units will be produced in FY2008. The MDA will review the project and should allow the project to proceed to MS C sometime in FY2010, if the program is determined to be successful. At this time Phase III (production and deployment) will begin. Low-Rate Initial Production (LRIP) should also begin in FY2010, and should consist of a total of seventeen units being produced (i.e. UHV's for four systems and five spare units). The production phase will begin with the LRIP and continue until FY2025, with IOC being reached in FY2012. Unless a decision is made to cancel the program early or extend it past the program life expectancy, disposal will begin in FY2030 and continue through FY2035.

A list of all statutory and regulatory requirements that need to be considered during each phase, but not necessarily met before proceeding to the next phase, depending on the type of acquisition program put in effect, can be found in Appendix C. (DoD Staff)

### 3.4 Life Cycle Costs

The total life cycle cost for one UHV or unit was estimated to be $7,200,000. (Note that all cost figures are for FY02, unless stated otherwise.) This was determined using an informal rule based on historical experience. The production cost of a fixed wing aircraft is directly proportional to its empty weight (i.e. before mission equipment is added). (USD & ASD

Staff) A figure of $1500 per pound (based on FY94 dollars) was adjusted for inflation for FY02 to be approximately $1800 per pound. (Woodrow) Using the assumed desired weight of 1000 lbs. resulted in a production cost of $1,800,000 per unit. This cost was then multiplied by the 300 total units, requested by the customer, in order to determine the production cost for the entire program. This resulted in an estimated cost of $2,160,000,000 for the total life cycle of the program.

Table  lists the breakdown of total life cycle cost for the program. Also shown is the estimated total cost per unit. The total cost was broken down as follows. Ten percent of the total cost was assumed to be Research, Development, Test, and Evaluation (RDT&E), twenty-five percent was assumed for production, and sixty-five percent was assumed for O&S. Disposal cost typically represents a small fraction of the total life cycle cost and was therefore excluded (Gunther). Figure 23 illustrates the life cycle phases and how they relate to the total life cycle cost.

Table 10 Life Cycle Cost Per Unit

| Costing Phase | Percent of Total Cost | Total Program Cost ($) FY02 | Unit Cost ($) FY02 |
|---|---|---|---|
| RDT&E | 10 | 216,000,000 | 720,000 |
| Production | 25 | 540,000,000 | 1,800,000 |
| O&S | 65 | 1,404,000,000 | 4,680,000 |
| Disposal | n/a | n/a | n/a |
| **Total** | 100 | 2,160,000,000 | 7,200,000 |

Figure 23: Program Life Cycle (OSD)

Using the tentative production and deployment schedule seen in Table 11, the minimum estimated amount of funding needed for the FY's shown was determined and can be seen in Table 12 below. Note that RDT&E and production costs only include the UHV's and not the extra equipment needed to field a fully operational system. All units will not be produced,

nor will all systems be deployed in the FY's shown. Rather, they will be produced and distributed over several years. All of the funding necessary for production and deployment may be appropriated at one time in the FY's shown.

Table 11 Tentative Production and Deployment Schedule

| FY for Production and Deployment to Begin | Schedule Activity | UHV's Produced | UHV Spares Produced | Systems Deployed |
|---|---|---|---|---|
| 2008 | Prototypes | 2 | 0 | 1 |
| 2010 | LRIP | 12 | 5 | 4 |
| 2012 | IOC | 45 | 16 | 15 |
| 2015 | Full Rate Production & Deployment | 75 | 26 | 25 |
| 2020 | Full Rate Production & Deployment | 90 | 31 | 30 |
| Total | --- | 224 | 78 | 75 |

Table 12 Funding Necessary to Fulfill Production/Deployment Schedule

|  | FY2008 ($) | FY2010 ($) | FY2012 ($) | FY2015 ($) | FY2020 ($) |
|---|---|---|---|---|---|
| UHV's | 5,040,000 | 21,600,000 | 81,000,000 | 135,000,000 | 162,000,000 |
| Spares | 0 | 9,000,000 | 28,800,000 | 46,800,000 | 55,800,000 |
| Systems | 18,720,000 | 74,880,000 | 280,800,000 | 468,000,000 | 561,600,000 |
| Total | 23,760,000 | 105,480,000 | 390,600,000 | 649,800,000 | 779,400,000 |

The total estimated life cycle cost of the program ($2,160,000,000), when evenly distributed over thirty years, results in an annual budget of approximately $72,000,000. More funding per year may be needed during the first ten years of development and less per year during the disposal phase.

Total life cycle cost estimates will need to be reviewed and revised as necessary at each milestone decision review (OSD). Funding will come from the budget of the Department of the Army and can be divided among several budgetary items such as Research and

Development (R&D), Tactical Unmanned Ground Vehicles, Tactical Unmanned Aerial Vehicles, etc. Other branches of the military may also fund R&D for new technology with cross-service applicability (USD & ASD Staff).

## 3.5 Risk Analysis

A historical basis was used to determine areas of risk that need to be considered. The Israeli military, prior to April 2001, conducted a study of its UAV mishaps after accumulating 80,000 hours of operations. (In comparison, the U.S. military had accumulated 50,000 hours of operations at that time.) Figure 24 shows the breakout of responsibilities for the mishaps. It was found that the propulsion, flight control system, and operator error accounted for 75 percent of all mishaps (USD & ASD Staff).
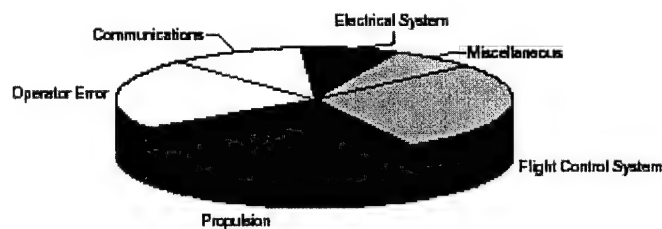


Figure 24: Israeli UAV Mishap Causes

Concentrating on these three areas early in the concept phase could significantly reduce the overall attrition rate and acquisition cost. Exploring new technologies and conducting tradeoff analysis for the propulsion, flight control system, and communications could reduce operation and support costs while increasing the reliability of the UHV. Designing the UHV to be fully autonomous could reduce operator error to near zero. This is due to the fact that software based performance is guaranteed to be repeatable, and software can be modified after an accident to remedy the situation causing the mishap. Again tradeoffs would have to be made, since current software technology needed to make the UHV fully autonomous may be too expensive to develop (USD & ASD Staff).

The potential savings from identifying and making improvements in the propulsion, flight control system, and operator error make a strong case for concentrating on these areas during the concept and development stages of the UHV.

## 3.6 Discussion of Application and Feasibility

The UHV design that is eventually produced and deployed will combine the capabilities currently performed separately by UAV's and Unmanned Ground Vehicles (UGV's). This will reduce O&S costs significantly, by reducing the number of personnel and the amount of training currently needed to field both UAV's and UGV's. The UHV will have an advantage in certain mission areas commonly categorized as "the dull, the dirty, and the dangerous." That is, it will be able to monitor a much larger area than human sentries ("the dull") and thus become a force multiplier. It can be used to detect for nuclear, biological, or chemical (NBC) contamination without risk to human life ("the dirty"). The UHV will also be capable

of assuming risky missions and can be used to prosecute heavily defended targets (currently left to forces on the ground or in the air) without loss of human life ("the dangerous"). In short, the opportunities available in effectively deploying the UHV are subject only to the imagination of the commanders. (USD & OSD Staff)

The UHV will probably cost as much to develop as current manned air and ground vehicles. However, the cost of the UHV will be significantly cheaper over the entire life cycle. This is due to the fact that personnel can be sufficiently trained with simulators, unlike currently manned vehicles where some losses occur during training. There is no threat to the personnel if the UHV is lost during a mission. This will reduce the number of crews that have to be trained as replacements, thus saving time and money. (USD & OSD Staff)

# 4.0 Company Capabilities

## 4.1 Company Overview

The J5 Engineering team is composed of eight students from UAH and three students from ESTACA. These students capitalized on Internet community building experience from the team lead to effectively communicate over the course of the project. J5 Engineering staffers made excellent use of the knowledge and experience of technical mentors from AMCOM and Snecma to develop their concepts and their understanding of the underlying technologies that make this UHV possible.

Over the course of the semester, the J5 Engineering team made use of the Internet, especially the team Web site at http://www.iptmadness.com/team1/ as a communication and information-sharing tool. The team Web site could be used to transfer data back and forth between team members, and a complementary email discussion list was used to ensure commonality of data/knowledge transfer amongst team members.

Members of the J5 Engineering team worked with the customer during all phases of development to develop a reasonable specification for the UHV. The team lead interacted directly with the AMCOM customer representative, Mr. Jim Winkeler, when discussions proved necessary. Every J5 Engineering staffer made positive contributions to the overall specification development process.

J5 Engineering includes of the following eleven individuals, with the following talent base:

## 4.2 Personnel Description

- Ms. Florence Bert – J5 Engineering Air Propulsion Engineer
  Ms. Bert's background in air propulsion systems has enabled J5 Engineering to select a reasonable engine for the air side of the system. Ms. Bert headed the Phase I group from ESTACA and carried forth those leadership skills for the remainder of the competition.

- Mr. Forrest Collier – J5 Engineering Aerodynamicist

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Mr. Collier's background in aerodynamics combined with his military experience in the United States Marine Corps make him a valuable asset. Mr. Collier's can-do attitude makes him a valuable team member.

- Ms. Jamie Flynt – J5 Engineering Lead Systems Engineer
  Ms. Flynt's background in systems engineering from previous design practices allow her to effectively encourage synthesis among the design team. Her excellent communication skills and overall knowledge of the vehicle make her an important part of the team.

- Ms. Claire Lessiau – J5 Engineering Ground Power Engineer
  Ms. Lessiau's background in the development of electrical power systems make her an extremely valuable team member. Her experience with fuel cell technologies in the research arena led to our key developments in this regard.

- Mr. Jason Maycock – J5 Engineering Ground Robotics Engineer
  Mr. Maycock's experience as a general mechanical engineer combined with his language skills made him an extremely important team member. He was consistently able to communicate his ideas to others and to break down barriers of communication between other team members.

- Mr. Shane Mills – J5 Engineering Mission Simulation Engineer
  Mr. Mills's background in mechanical engineering and balancing the needs of a diverse set of people from a manufacturing environment led well into his work in developing a mission simulation analysis. His solid work ethic is a credit to the team.

- Mr. Geof Morris – J5 Engineering Team Lead
  Mr. Morris's extensive background in leadership at the University of Alabama in Huntsville made him a strong choice for leadership of the team. His ability to organize chaos helped keep the team going in rough times.

- Ms. Isabel Ortega – J5 Engineering Avionics and Sensors Engineer
  Ms. Ortega's background as a computer engineer made her a solid choice for one of our two avionics engineers. Her background as a non-native English speaker made interaction with the members from ESTACA much easier.

- Mr. Kari Salomaa – J5 Engineering Structural Engineer
  Mr. Salomaa's background in construction techniques served the team well in developing concepts for the fabrication of the fuselage. Mr. Salomaa's background as a non-native English speaker also assisted in communications with the ESTACA members of our team.

- Ms. Teresa Samuels – J5 Engineering Avionics and Sensors Engineer
  Ms. Samuels's background as a computer engineer also made her a solid choice for an avionics engineer. Her ability to work with a limited knowledge set made her a valuable asset in gleaning information from a highly-competitive and often highly-classified field.

- Mr. Alexandre Tellier – J5 Engineering Transmission Engineer
  Mr. Tellier's background in designing transmissions made him a natural choice for our transmission designer. His enthusiasm and work ethic are second to none on the J5 Engineering team.

## 5.0   Summary and Conclusions

In summary, J5 Engineering feels this proposal is the best solution possible. The Choctaw UHV provides a comprehensive solution that merges a proven air power system—a coaxial rotorcraft powered by a diesel engine—with a ground system that uses time-tested concepts for ground maneuverability in skid-steering with fixed wheels. While the basic principle of the Choctaw UHV is very similar to the baseline design developed by the Superteam in Phase I of the IPT competition, it differs in a few key areas:

- Selection of a reasonable powerplant that uses heavy fuels has made the vehicle more acceptable to the customer.
- Rather than using batteries in a traditional approach to providing electrical power to the ground and avionics portions of the vehicle, the Choctaw uses a fuel cell that is sized to the average power needs of the vehicle and a set of two ultracapacitors that provide power at times of peak need.
- Blades that automatically fold reduce crew turnaround time on the ground and allow for greater maneuverability in the ground portion of the mission.
- A superior avionics and sensor suite has been developed for use in the Choctaw when compared to the baseline.
- The total package weight of the UHV, including palettes, shipping containers, and the ground station, comes in at 10% under the maximum allowable system weight.

## 6.0   Recommendations

In developing this design, the J5 Engineering team realizes the concept is unlikely to be used as anything more than a vague concept for the development of a true first-generation UHV. As such, we feel that we should make recommendations to the customer, the United States Army Aviation and Missile Command, regarding the specifications laid forth in the concept description document.

- A reasonable base of operations should be laid out to give the designers an idea of the true operational range. Any UHV is not likely to be launched near the FLOBT, but it could be launched from near the front or deep behind friendly lines. Any significant variance in this range affects the operational range greatly, as the fuel load by the UHV will vary depending upon that range.
- A greater sense of the mission to be carried out would help the designers. For example, delivery of critical cargo could be anything from landing and maneuvering a few units of blood to a mobile army surgical hospital to dropping ammunition to a pinned-down unit under heavy fire. The Choctaw UHV requires that a crewmember

be present to offload cargo, but this may not be feasible in all flight regimes. An idea of the threat environment likely to be faced would significantly help the designer.

- A clearer sense of the biological and chemical detection mission should be available to the designer. J5 Engineering staffers are aware of the constraints of presenting such a sense to a group of college students without security clearances—and, for nearly half of our team, U.S. citizenship.
- It might be feasible to allow the UHV to be towed along behind the HMMWV rather than be placed inside the trailer for towage. One design considered by the J5 Engineering team would have been feasible if the vehicle could have been larger. The UHV does have ground maneuverability, and this could be capitalized in the grand scheme of the logistics train.
- The UHV could also be considered a targeting platform for close air support strikes. Provision could be made in the specification for the ability to communicate with a military standard target recognition, classification, and handoff system.

The J5 Engineering team would like to take this space to thank the review team for their time and consideration. We would also like to thank AMCOM for providing a challenging design problem. Special thanks go to Mr. Jim Winkeler, who led the AMCOM effort.

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# Appendix A: Concept Description Document
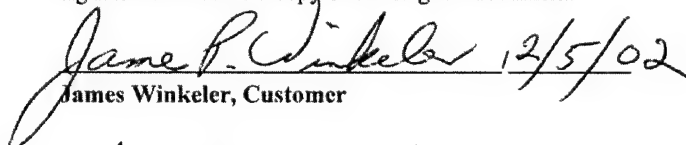
## Appendix A - Concept Description Document
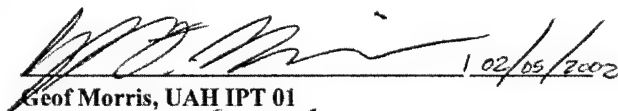
**Concept Description Document Approval**
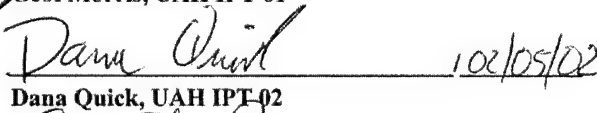
The undersigned agree that the attached Concept Description Document as marked will be the basis the UAH IPT 2002 Design Competition. From this time forward, any questions or clarifications concerning the concept description document to the Customer shall be submitted in writing and the answer distributed to all UAH IPT's in writing.
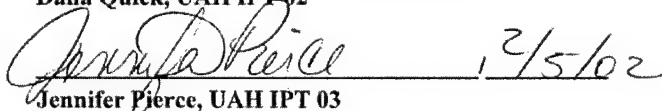
To change the Concept Description Document Prior to April 30, 2002 shall require that the change be stated in writing and that a person authorized by every one of the signers below endorse the change with their signature. The revision will be labeled uniquely and distributed to all teams simultaneously.

The original of this document will be kept on file with the UAH Project Director. All signers will receive a copy of the original document.

_James P. Winkeler_ 12/5/02

**James Winkeler, Customer**

_Geof Morris_ 02/05/2002

**Geof Morris, UAH IPT 01**

_Dana Quick_ 02/05/02

**Dana Quick, UAH IPT 02**

_Jennifer Pierce_ 2/5/02

**Jennifer Pierce, UAH IPT 03**

_Robert A. Frederick Jr._ 2/5/02

**Robert A. Frederick, Jr., UAH IPT 2002 Project Director**

## Appendix A - Concept Description Document

1. General Description of Operational Capability
   1.1. Overall Mission Area
   1.1.1. The system shall be a versatile scout and pack animal for future force structures, transporting critical payloads (e.g., ammunition, medical supplies).
   1.1.2. The system shall be capable for use for target recognition and definition.
   1.1.3. The system shall be capable for use in terrain definition.
   1.1.4. The system shall be capable for use in situational awareness.
   1.1.5. The system shall be capable of at least semi-autonomous operation, with full autonomous operation desirable.
   1.1.5.1. The system shall be capable of human interface as required.
   1.1.6. The system shall be capable of executing both a preplanned and diverted mission profiles.
   1.1.7.       The system shall be capable of navigating and functioning without a payload.
   1.1.8.       The system shall be capable of detecting chemical and biological threats.
   1.1.9.       The system shall be capable of detecting adverse weather conditions.
   1.2. Operational Concept
   1.2.1. The system shall be capable of nap of the earth flight (below the treeline).
   1.2.2. The system shall be capable of operation at a range of 15-30 km ahead of the fighting force, with a 10% fuel reserve upon return.
   1.2.2.1. The system shall be capable of gathering information on threat activities at range.
   1.2.2.2. The system shall be capable of enhancing the RISTA/BDA.
   1.2.2.3. The system shall be capable of transmitting information via secure data links and C2 structures BLOS.
   1.2.2.4. The system shall be capable of using TF/TA/GPS/INS hardware and software to define and navigate complex terrain.
   1.2.2.5. The system may encompass a degree of AI, ATR, and on-board decision making.
   1.2.3. Payload Requirements
   1.2.3.1. The system shall be capable of carrying a payload of 60lbs required gross weight, 120lbs desired gross weight, with a minimum payload volume of 2' x 2' x 2' [8 ft$^3$].
   1.2.3.2. The system shall be capable of flying the payload to operational range in 30 minutes or less and be able to return from range in 30 minutes or less.
   1.2.3.2.1. The vehicle will have a minimum cruise airspeed of 30 km/hr and a desired airspeed of 100 km/hr.
   1.2.3.3 There shall be no power or data interfaces between the vehicle and the payload.
   1.2.4. Mission Requirements
   1.2.4.1. The system shall be capable of landing in an unprepared area with a ground slope of 12° maximum up or down.
   1.2.4.1.1. The vehicle must have vertical takeoff and landing capabilities.
   1.2.4.2. The system shall maximize survivability.

1.2.4.2.1. The system shall have a near quiet acoustic signature.

1.2.4.2.2. The system shall be designed for an operational altitude of 0 – 250 ft AGL required, 0-500 ft AGL desired.

1.2.4.2.3. The system shall be capable of a 200 fpm VROC [required], 500 fpm [desired], at 4000 ft and 95 °F, with the payload in place.

1.2.4.3. The system shall be designed to be transported via a HMMWV and trailer, and/or via external sling load by a UH-60 helicopter.

2. System Capabilities

   2.1. The system shall be capable of operation at an altitude of 4000ft, 95 degrees Fahrenheit ambient temperature, and not using more than 90% maximum rated power.

   2.2. Operational Performance

      2.2.1. The system shall possess essential performance, maintenance, and physical characteristics required to operate under adverse environmental conditions worldwide, down to –40 °F.

      2.2.2 The system shall possess essential performance, maintenance, and physical characteristics required to operate under adverse geographical conditions worldwide.

      2.2.3. The system shall be capable of operating from any unimproved land facility surface day or night, including low illumination.

      2.2.4. The system shall be capable of operation under and detection of battlefield obscurants.

      2.2.5. The system shall be capable of ground operations on unimproved roads at ground speeds of 6 km/hr [required], 12 km/hr [desired] for no less than two (2) hours at a radius of 0.5 km [required], 1 km [desired]. Unimproved roads: Non-prepared surfaces, not to have more than RMS of 1", which means, over 1 ft can not rise or dip more than one inch, no linear features, which means no barriers, blocks, bricks, big rocks, etc., nothing in path of vehicle except trail or road and finally, no more grade than 12 degrees.

      2.2.6. The system [vehicle and ground station] shall weigh no more than 1500 lbs [required], 1000 lbs [desired].

      2.2.7. The system shall use readily available diesel or jet fuel.

   2.3. The system shall possess the following electronic capabilities:

      2.3.1. Mission Planning System

         2.3.1.1. The system shall possess a point-and-click pre-mission planning system to simulate mission flight.

         2.3.1.2. The system shall possess data loading capabilities.

         2.3.1.3. The system shall be capable of coordination and reaction to immediate operational mission changes.

         2.3.1.4. The system shall be capable of processing self awareness and threat sensor inputs.

         2.3.1.5. The system shall be capable of enabling TF/TA from digital mapping information from satellite or other sources.

      2.3.2. Avionics

2.3.2.1. Communications and navigation suite architecture shall be compatible with emerging military data links.

2.3.3. Communications

2.3.3.1. System communications shall be robust and have clear secure modes of operation

2.3.3.2. Communications shall be simultaneously LOS and BLOS which can include satellite relay or other relay system compatibility.

2.3.3.3. System must posses IFF and be compliant to all FCC/military communication regulations.

2.3.3.4. System must be capable of communication with and sharing digital mapping/targeting information with other DoD RISTA platforms.

2.3.4. Connectivity

2.3.4.1. The system shall be interoperable with other DoD systems envisioned for the 2012 battlefield to the maximum extent possible and be compatible with service unique command, control, and information systems.

3.0    ACRONYM LIST

| | |
|---|---|
| AGL | Above Ground Level |
| AI | Artificial Intelligence |
| ATR | Automatic Target Recognition |
| BDA | Battlefield Damage Assessment |
| BLOS | Beyond Line of Sight |
| C2 | Command and Control |
| DoD | Department of Defense |
| FCC | Federal Communications Commission |
| fpm | feet per minute |
| ft | feet |
| GPS | Global Positioning System |
| HMMWV | High-Mobility, Multipurpose Wheeled Vehicle |
| IFF | Identify Friend or Foe |
| INS | Inertial Navigation System |
| IPT | Integrated Product Team |
| km | kilometers |
| km/hr | kilometers per hour |
| lbs | pounds |
| LOS | Line Of Sight |
| RISTA | Reconnaissance, Intelligence, Surveillance, Target Acquisition |
| RMS | Root Mean Square |
| TA | Terrain Avoidance |
| TF | Terrain Following |
| UAH | The University of Alabama in Huntsville |
| UH-60 | Utility Helicopter |
| VROC | Vertical Rate Of Climb |

## Baseline Mission Profile

**Critical Flight Conditions:**
Altitude - 4000 ft
Temp - 95ºF
VROC – 200-500 FPM

**Segment 4**
Cruise Outbound
ALT NOE-250 ft
Velocity 0-30
km/hr

**Segment 10**
Cruise Inbound
ALT NOE-250 ft
Velocity 0-30
km/hr

**Segment 3**
Climb to Combat
Operational
Altitude
VROC 200 FPM

**Segment
5**

**Segment 9**
Climb to Combat
Operational
Altitude
VROC 200 FPM

**Segment
11**

**Segment 1**
Engine
Start

**Segment 7**
Ground Maneuver
Radius 0.5 km

**Segment
2**

**Segment
6**
Hover and

**Segment 8**
Repeat Segments
2-7 as Required

**Segment 12**
Hover
Land
10% Fuel
Reserve

# Appendix B: White Paper

The white paper presented at the completion of Phase 2 of this design competition can be found on the following pages.

# *Competition Sensitive Document Attached*

## Team 1

**The Attached Document is Competition Sensitive until May 1,2002.**

**If you find this document and do not know what to do with it,**

**put it is a secure place and notify**

*Dr. Robert A. Frederick, Jr. at UAH*

*256-824-7203*

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# Final

# Alternate Concepts White Paper

# IPT 1

| | |
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| Propulsion and Power | Florence Bert, Claire Lessiau, Alexandre Tellier |
| Ground Robotics/Vehicle | Jason Maycock |
| Mission Simulation | Shane Mills |
| Mechanical Configuration/Structures | Kari Salomaa |
| Avionics, Sensors, Autonomous Flight Controls | Isabel Ortega and Teresa Samuels |
| Programmatic Considerations | Geof Morris |

Submitted By:

# J5 Engineering

Team Web Page: http://www.iptmadness.com/team1/

March 5, 2002

# Abstract

Today's battlefield is a fast-moving, competitive environment where the stakes are life—or death. The most powerful weapon in a commander's arsenal is information. Reconnaissance and intelligence gathering are the most reliable routes to garner information. Recent advances in communications and robotics allow military designers to envision platforms to gain such information without putting lives at risk. In this light, J5 Engineering at The University of Alabama in Huntsville [UAH] and Ecole Supérieure des Techniques Aéronautiques et de Construction Automobile [ESTACA] are involved in the development of a conceptual design for an Unmanned Hybrid Vehicle [UHV] that takes elements of existing Unmanned Air Vehicles [UAV's] and Unmanned Ground Vehicles [UGV's] and synthesizes them into one vehicle.

Three concepts were compared to the baseline design undertaken by the entire MAE 464/465 Integrated Product Teams class. J5 Engineering developed an advanced version of the baseline design, the "Seagull"; a centrally mounted ducted fan approach, the "Fighting Duct", and a hybrid-powered diesel and fuel cell coaxial rotorcraft called the "Choctaw". J5 Engineering members evaluated each concept with relation to the baseline: the "Fighting Duct" lived up to its name given the size constraints placed upon the UHV by the transportation requirements, and the "Choctaw" ended up as a superior design to the "Seagull".

# Resumé

Le champ de bataille de today.s est une condition de concurrence rapide et où les pieux sont la mort de life.or. L'arme la plus puissante dans un arsenal de commander.s est l'information. Le rassemblement de reconnaissance et d'intelligence sont les itinéraires les plus fiables à l'information de garner. Les avances récentes en transmissions et robotique permettent aux créateurs militaires d'envisager des plateformes pour obtenir une telle information sans mettre les vies en danger. J5 ingénierie université Alabama dans Huntsville [ UAH ] et Ecole Supérieure DES technique Aéronautiques et De Construction Automobile [ ESTACA ] impliquer dans développement un conceptual plan d'étude pour un non-piloté hybride véhicule [ UHV ] ce prise élément existant non-piloté air véhicule [ UAV.s ] et non-piloté moulu véhicule [ UGV.s ] et synthétiser les dans un véhicule.

Trois concepts ont été comparés à la conception de ligne de base entreprise par la classe intégrée d'équipes de produit de MAE 464/465 entier. L'ingénierie J5 a développé une version avancée de la conception de ligne de base, le Seagul.; une approche canalisée central-centrally-mounted de ventilateur, le Fighting Duct, et un rotorcraft coaxial hybride-hybride-powered de cellules de diesel et de carburant ont appelé le Choctaw. Les membres de l'ingénierie J5 ont évalué chaque concept en ce qui concerne la ligne de base: le tuyau de Wounded a vécu jusqu' à son nom donné les contraintes de taille placées sur l'cUHV par les conditions de transport, et au Choctaw terminé vers le haut de comme conception supérieure au Seagull.

# Technical Description

**B1.0 Overview of Phase 2**

The Unmanned Hybrid Vehicle [UHV] sought by the U.S. Advanced Systems Directorate is envisioned to provide essential scouting and target recognition to the Brigade Commander. The customer and all participating teams endorsed a Concept Description Document [CDD] finalizing the customer requirements for this system on February 5, 2002. Phase 1 of the project produced one baseline concept that attempted to satisfy the project [CDD] using existing technology. J5 Engineering at the University of Alabama in Huntsville has focused on synthesizing three alternative concepts. This White Paper provides a summary of the Baseline and our three alternative concepts. The key attributes of each concept are compared against the CDD. One of the concepts is selected for development in Phase 3.

B1.1 Specification Summary

The UHV must perform both air and ground missions in its overall flight profile. The UHV must travel a minimum of 15km beyond the Forward Line of Troops [FLOT] at an airspeed of no less than 30 km/hr in an hour's time. The UHV must then perform a ground mission of two hours at a ground speed of no less than 6 km/hr while traveling in a radius no less than 0.5 km from the landing site. The UHV must then perform a similar air mission the return flight home.

In performing these missions, the UHV must operate in a semi-autonomous manner, with a maximum of one crewmember responsible for controlling the flight via a communications link. The system must be capable of beyond line of sight [BLOS] communications to the ground station. The missions performed can include detection of biological and chemical warfare, delivery of critical cargo, terrain definition, reconnaissance and intelligence gathering, and improving the battlefield situational awareness. The system must employ navigation using the Global Positioning System [GPS] and/or an Inertial Navigation System [INS], and must employ Terrain Avoidance [TA] and Terrain Following [TF] for nap of the earth flight at 250 ft AGL.

B1.2   Key Challenges

The key challenges of this design project involve merging the ground and air portions of the system. As seen in the recent conflict in Afghanistan, UAV's are a mature flight platform for the reconnaissance and intelligence-gathering missions for which they were designed. UGV's are an emerging technology, allowing a ground commander to employ these vehicles in high-threat situations to get a better idea of the forward area. However, previous UAV's have tended to be fixed-wing vehicles, and most UGV's have employed tracks in order to maneuver over potentially treacherous terrain. Combining the two vehicles into one and placing additional transportation requirements that limit the overall size of the vehicle make developing this design intellectually stimulating and challenging.

**B2.0 Description of Concepts**
In addition to the baseline design developed by the MAE 464/465 class, the Rolling Feather, J5 Engineering members developed three concepts to study various technological paths. In a conservative vein, J5 Engineering proposed the Seagull, which differed from the Rolling Feather in employing tracks for ground transport, a larger rotor to reduce engine requirements, spring-loaded blades to allow for a smaller ground profile, and a greater gross vehicle weight in the development of the concept. J5 Engineering members also proposed an outside-the-box concept, the Fighting Duct, which uses an internally mounted ducted fan for lift and two small turboprops for forward flight. The Fighting Duct also uses tracks for ground maneuvers. The final concept, the Choctaw, is similar to the Seagull and the Rolling Feather in that it is a coaxial rotorcraft. Like the Rolling Feather, the Choctaw uses wheels for ground maneuvers. However, the Choctaw employs a hybrid power source: a fuel cell drives the air and ground missions, with a diesel-powered engine in reserve for times when extra power is needed for the air mission.

B2.1 Baseline Concept "Rolling Feather"
The baseline concept was designed to meet the original specifications set forth by the customer. Some concept operations that the customer has in mind are reconnaissance missions that take place around 30 km in front of a fighting force, capable of collecting data, detecting chemical/biological weapons, and to transport payloads to dangerous parts of the battlefield.

The "Rolling Feather" consists of 14-foot folding coaxial rotors. The coaxial rotor concept was chosen to eliminate the torque of the rotor without the use of a tail rotor. The coaxial rotors allow the entire engine power to be used to produce lift where a tail rotor decreases to amount of engine power that is used. With a coaxial rotor design the Unmanned Hybrid Vehicle (UHV) will be able to perform flatter turns than with a tail rotor and gives the goal of a compact design. The IO-240B engine was chosen to power the coaxial rotors. This engine provides the needed amount of power along with a good fuel consumption rate.

The ground mechanism consists of four electrically powered wheels. Each wheel has a 2-hp motor mounted to it to give the required power to turn the 10-inch wheels. Batteries supply the required power inputs for each motor. The entire weight of the ground system is approximately 200 pounds. The UHV contains a cargo space that is located at the center of gravity of the vehicle. The entire weight of the UHV design is around 1100 pounds.

### B2.2 Concept 1A "Seagull"

Seagull is a strategically tuned, absolutely resilient structure designed to withstand the rigors of tomorrow's battlefields. . Please reference Fig. 2 on Page 9 for a visual representation of the concept. Seagull is an unmanned coaxial rotorcraft designed to take off vertically. Seagull has rotor diameter of 15 ft with aspect ratio not exceeding 18. The blades are constructed out of carbon fiber composite and are designed to fold automatically using a spring mechanism. The angular momentum will cause the blades to unfold while the rotor is spinning. It is powered by a 200-hp diesel engine that uses same fuel that is used in many military vehicles.

Conventional batteries that run electric motors attached to wheels that run tracks power the ground mission. The weight of the craft is 1500lbs. Seagull uses tracts to move in the ground. The fuselage is made of lightweight composite material. Reinforcement panels are placed around sensitive areas in the vehicle; materials such as Kevlar are used.

Seagull's fuselage is 5.5ft long and 3.5ft wide. It has hooks in its fuselage for transportation purposes by helicopter. It will fit on a HMMWV trailer. Seagull is arguably the best motor powered unmanned vehicle ever built. This machine is designed to perform night missions as well and it has infrared sensor devices. In case of biological warfare, Seagull will be able to make detect various chemicals and inform ground troops of the possible threat.

### B2.3 Concept XB "Fighting Duct"

The "Fighting Duct" makes use of a ducted fan concept coupled with turboprops for flight and tracks for ground operations. Please reference Fig. 3 on Page 10 for a visual representation of the concept. The "flying wing" configuration of the vehicle will provide a low profile that will reduce drag in air operations and provide for better cover and concealment in ground operations.

A single co-axial, ducted fan is positioned in the center of the "flying wing" and is used solely for hover and climb. The use of the co-axial ducted fan will eliminate the need for a separate counter-torque device to be implemented into the system thus conserving space. Two shrouded turboprops positioned on both sides at the rear of the vehicle provide thrust for forward flight. The ducted fan and turboprops will also be the means for controlling roll, pitch, and yaw. Conventional, diesel engines will be used to provide power for the flight propulsion systems.

Three, individually powered tracks will be used for ground operations. Two tracks are positioned on opposite sides at the rear of the vehicle and the third track is positioned in the middle at the front of the vehicle. Skid steering will be employed by the tracks in order to provide directional control for movement on the ground. The tracks are positioned close to the body of the vehicle. This will further enhance the vehicle's low profile and reduce drag in flight. Fuel cells will be used to power the electric motors driving each of the tracks. The electric motors will provide lower noise in ground operations and will enhance the cover and concealment abilities of the vehicle when it is most prone.

Avionics sensors are located in the nose of the vehicle and will provide for semi-autonomous flight and ground operations. The payload section is located in the rear of the vehicle between the two turboprops and will provide rear entry to the payload that can be easily accessed from the ground in order to provide for a variety of operations.

There are several advantages to selecting this concept. All of the technology required to build and implement this vehicle is readably available and should make the production specification quite accessible. The fact that the vehicle maintains a low profile and it's design eliminates vulnerable control devices such as rudders, produces a vehicle that will be better suited to the combat mission environment. Using tracks as the means of ground propulsion will also help to improve the performance of the vehicle by allowing passage over rougher terrain.

However, the disadvantages present with this system may keep the vehicle from meeting the spec. The main concern is the weight of the vehicle. Because the ducted fan cannot be larger than the width of the HMMWV trailer, there will have to be a very powerful engine implemented in order to obtain the thrust of around 370 lbs sufficient for hover and climb. In addition, two more power plants will have to be implemented in order to drive the two propellers in forward flight. The coupled weight of these three power plants together with all the other components of the vehicle will make the vehicle fail the weight specification set aside by the CDD.

The main concern is if the vehicle is built to fit the size requirements, then the performance specifications will not be met. If the vehicle is built to obtain a desirable performance, then the size specifications will be compromised.

B2.4 Concept XC "Choctaw"

The Choctaw will draw all of its operational power from Proton Exchange Membrane (PEM) fuel cells. Please reference Fig. 4 on Page 10 for a visual representation of the concept. Thrust will be generated by co-axial rotors driven by an electric motor and/or a diesel-power engine, connected in a parallel hybrid approach. The rotor disc will be 15 ft in diameter, with two blades of aspect ratio 18 for each rotor. Four individual 2-hp electric motors will provide power to the four wheels for extremely quiet ground maneuvers. Avionics and its sensors will guide the flight and navigation of the vehicle through nap of the earth flight paths and remote-controlled video operation will be available where communication conditions permit.

The Choctaw's primary advantages are its quiet operation and relatively quick warm-up period for beginning a mission. Its fuel requirement will need justification, as hydrogen is not a heavy fuel specified in the CDD. Fuel cell research has a large potential for the near future; until further density improvements are made, the weight of the fuel cell may become one of this system's biggest challenges.

The Choctaw does have some disadvantages. There is a certain amount of risk involved in developing a parallel hybrid concept. The transmission of power will be a difficult design

problem, and the size of the rotor makes transportation of the Choctaw a bit difficult. Proper design choices should minimize these disadvantages.

Each concept was compared to the baseline design using Table 1 below. Cells in Table 1 that are blank are areas in which the design was roughly comparable to the Rolling Feather. Cells that have a + in them denote areas where the design exceeded the capabilities of the Rolling Feather. Cells that have a – in them denote areas where the design was not as capable as the Rolling Feather. The most important factors were weighted as a 3, the important factors were given a 2, and all other factors were given a 1. Mission-critical requirements tended to receive the higher factors.

The Seagull was very similar to the Rolling Feather. It exceeded the Rolling Feather in the vertical rate of climb phase, due to the larger power reserve of its engine. It was worse than the Rolling Feather in transportability due to the increased rotor size, and the tracks provide more weight than is necessary for the ground system while not providing a significant increase in ground maneuverability.

The Fighting Duct was more of a wounded duct, receiving negative ratings across the board due to the size constraints placed upon the vehicle. If the Fighting Duct could be towed by a HMMWV rather than placed in the trailer, it might become a viable concept, as the vehicle could become larger and decrease the amount of engine power needed, thereby lowering the engine weight of the vehicles. Transportability was the only favorable comparison to the Rolling Feather, as no rotor blades extend past the envelope of the trailer.

The Choctaw received positive marks in ground speed [due to the use of wheels rather than tracks], endurance and range due the use of efficient fuel cells that should extend the range significantly [as the fuels are much lighter], weight [given that development can probably result in a lighter vehicle], and acoustic signature. It was considered less transportable than the Rolling Feather, and also received negative marks due to concerns over the specification requirements and the technological development risk.

In the end, J5 Engineering has selected the Choctaw parallel hybrid approach as the final concept to be pursued in Phase 3. We look forward to input from the Customer and the Review Team as to the feasibility of this concept.

**B3.0 Selection of Final Concept**

**B4.0 Phase 3 Plan**

B4.1 Key Issues to Address

The key issues to be addressed in further development of the Choctaw center around the fuel cell proposal. First, J5 Engineering must be reassured by the Customer and/or the Review Team that subverting the specification requirement for heavy fuels does not prohibit the use of fuel cells. Assuming that this is not an obstacle, the J5 Engineering team must then extrapolate the power output likely to be discovered in fuel cells manufactured in 2005 or 2006, develop a logistical plan for providing hydrogen and oxygen in pure, fluid form to the battlefield, and model a transmission system that will allow the parallel hybrid power source to provide the necessary power in all mission regimes.

J5 Engineering will confirm that the Choctaw's power source is acceptable to the Customer, and then will research fuel cell technology in order to determine the rate of power output advancement. J5 will develop a model for the parallel hybrid system that will use as much off-the-shelf components as possible, likely relying on the research in parallel hybrids performed by US automobile manufacturers under fiat of the Department of Energy. Cost issues will be researched, and the basis for a logistics plan will be developed in order to propose the vehicle as a viable option for the Customer.

B4.2 Phase 3 Schedule

## B5.0 Illustrations
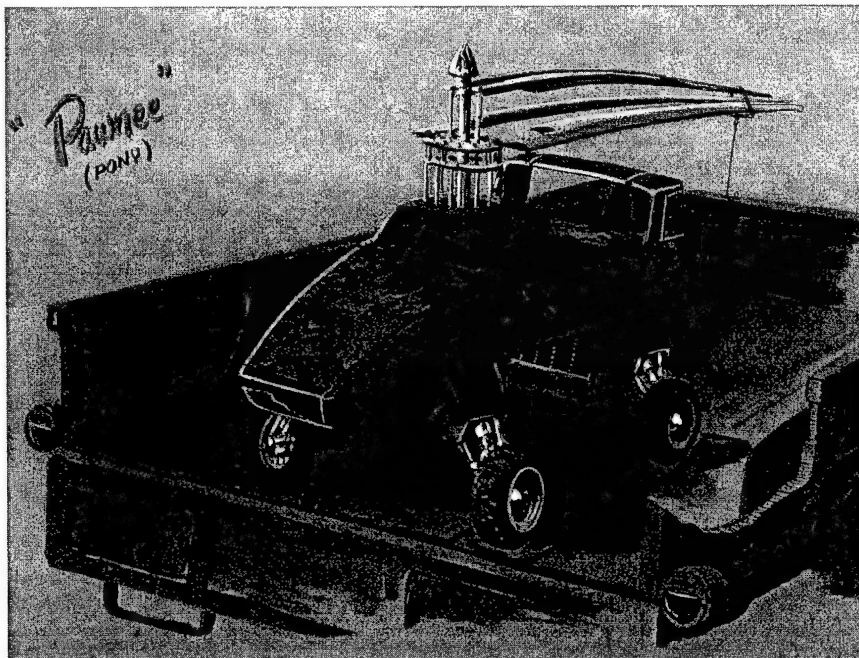


Figure 1. Baseline "Rolling Feather"
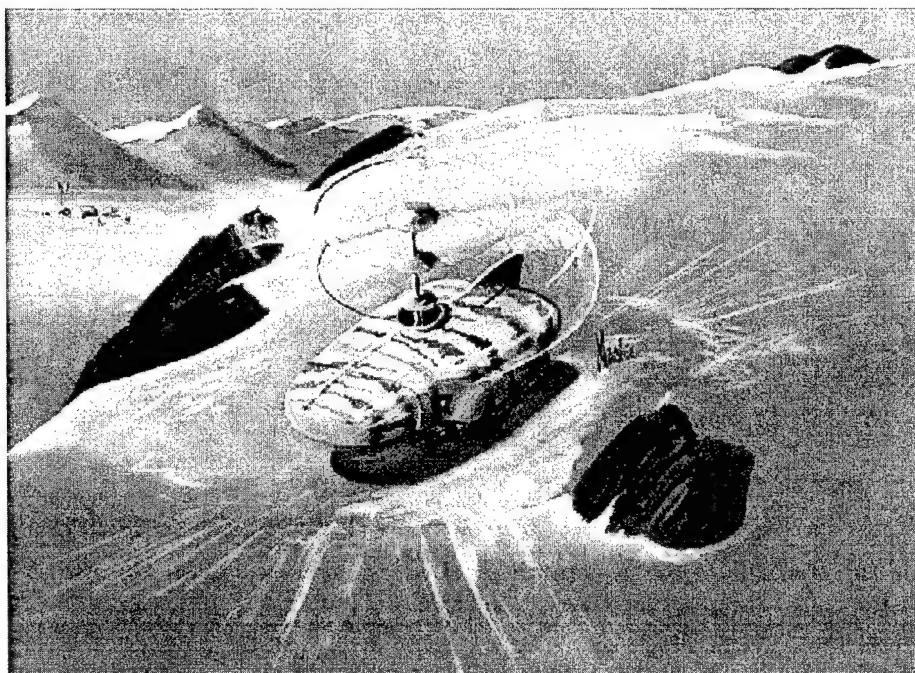


Figure 2. Concept 1A "Seagull"
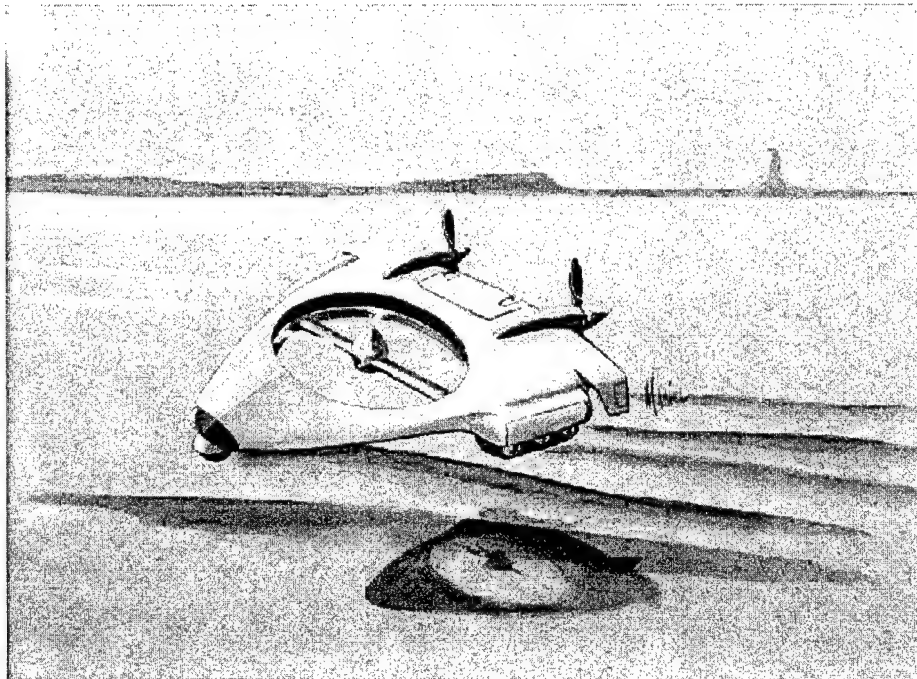
Figure 3. Concept 1C "Fighting Duct"



Figure 4. Concept 1D "Choctaw"

Table 1.  Concept Evaluation Matrix

| | Factor | Baseline | 1-A | 1-B | 1-C |
|---|---|---|---|---|---|
| **Required Attributes** | | Rolling Feather | Seagull | Fighting Duct | Choctaw |
| Airspeed, 30 km/hr | 2 | | | − | |
| Vertical Climb, 200 fpm | 2 | | + | − | |
| Ground Speed, 6 km/hr | 2 | | | − | + |
| Flight Profile, Hover-Full | 1 | | | | |
| Operational Altitude, 0-250 ft AGL | 2 | | | − | |
| Endurance, 4 hours | 3 | | | − | + |
| Payload, 60 lbs | 3 | | | − | |
| Range, 15 km | 3 | | | − | + |
| Operation, Semi-Autonomous | 3 | | | − | |
| Transportable, HMMWV, UH-60 | 1 | | − | + | − |
| Max Weight, 1500 lbs | 1 | | | − | + |
| **Team-Selected Decision Attributes** | | | | | |
| Meets Fuel Specification | 1 | | | | − |
| Ground System Type | 1 | | − | − | + |
| Acoustic Signature | 1 | | | | + |
| Technological Development Risk | 1 | | | | − |
| **TOTALS** | | *0* | *0* | *-21* | *8* |

Table 2.  Concepts Comparison

| **Common Engineering Criteria** | **Baseline** Rolling Feather | **1-A** Seagull | **1-B** Fighting Duct | **1-C** Choctaw |
|---|---|---|---|---|
| Air Configuration | Coaxial Rotor | Coaxial Rotor | Ducted Fan [Internal] | Coaxial Rotor |
| Ground Configuration | Wheels-rubber Golf Cart type | Tracked Wheels | Tracked Wheels | Wheels-rubber Golf Cart type |
| Payload Mass, kg (lb) | 27.2 kg (60 lb) | 27.2 kg (60 lb) | 27.2 kg (60 lb) | 27.2 kg (60 lb) |
| Assumed Gross Takeoff Weight. kg (lb) | 503 kg (1109lb) | 680 kg (1500 lb) | 680 kg (1500 lb) | 680 kg (1500 lb) |
| Aero Propulsion Type | Piston Engine | Piston Engine | Piston Engine | Piston Engine & Fuel Cell |
| Energy Source for Air Transport | AvGas 100 LL | Diesel 150 LL | JP-8 250 LL | Diesel 100 LL & H2 / O2 |
| Ground Propulsion Type | Electric Motors | Electric Motors | Electric Motors | Electric Motors |
| Energy Source for Ground Transport | Electric (Battery) | Electric (Battery) | Electric (Battery) | Electric (Fuel Cells) |
| Power to HOGE at 4k ft. - 95° F, kW (hp) | 64.9 kW (87 hp) | 59.7 kW (80 hp) | 335 kW (450 hp) | 59.7 kW (80 hp) |
| Cruise Power, kW (hp) | 39.5 kW (53 hp) | 35.8 kW (48 hp) | 283 kW (380 hp) | 35.8 kW (48 hp) |
| Basis of Autonomous control | none | none | none | none |
| Primary BLOS Method | Ground radio | Ground radio | Ground radio | Ground radio |
| Primary Navigation Method | GPS | INS | INS | GPS/INS |
| Primary Sensor Type | FLIR Camera | TF/TA Radar | FLIR Camera | TF/TA Radar |
| Enabling Technology | Existing | Existing | Existing | PEM Fuel Cells |

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# Word List

[The Project Officers from Each Team will meet with the instructor to develop a common list of words for all teams. This table at a minimum should make reference to the unique words or abbreviations used in your White Paper. The list below is an example from a Project Plan.]

AGL         Above Ground Level
BLOS        Beyond Line of Sight
            ESTACA  Ecole Supérieure de Techniques Aéronautiques et de Construction
                Automobile
FLOT        Forward Line of Troops
fpm         feet per minute
ft          feet
GPS         Global Positioning System
HMMWV       High-Mobility, Multipurpose Wheeled Vehicle
INS         Inertial Navigation System
IPT         Integrated Product Team
km          kilometers
km/hr       kilometers per hour
lbs         pounds
TA          Terrain Avoidance
TF          Terrain Following
UAH         The University of Alabama in Huntsville
UH-60       Utility Helicopter
VROC        Vertical Rate Of Climb

# Appendix C: Sample Calculations
## C1 – Mission Simulation

Baseline Mission Profile

| | | | | | Altitude | 500 ft | |
| | | | | | Start Elevation | 4000 ft | |
| | | | | | VROC | 200 ft/min | |

| SEGMENT # | DESCRIPTION | TIME (hr) | DISTANCE (Km) | AIRSPEED (Km/hr) | %Required Power | FCR (gallons/hr) | (gallons) | (lb) | FCR (lb/hr) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | WARM UP/IDLE | 0.08 | 0 | 0.00 | 7 | 0.53 | 0.04 | 0.26 | 3.074 |
| 2 | HOVER | 0.20 | 0 | 0.00 | 73.33 | 6.59 | 1.33 | 7.71 | 38.222 |
| 3 | CLIMB | 0.04 | 0 | 152.39 | 83.33 | 7.66 | 0.32 | 1.85 | 44.428 |
| 4 | CRUISE | 0.47 | 15 | 32.00 | 46.67 | 3.94 | 1.85 | 10.71 | 22.852 |
| 5 | DESCENT | 0.04 | 0 | 152.39 | 43 | 3.6 | 0.15 | 0.87 | 20.88 |
| 6 | HOVER/LAND | 0.20 | 0 | 0.00 | 73.33 | 6.59 | 1.33 | 7.71 | 38.222 |
| 7 | GROUND (ELECTRICAL) | 2.00 | 0 | | | | | | |
| 8 | WARM UP/IDLE | 0.08 | 0 | 0.00 | 7 | 0.53 | 0.04 | 0.26 | 3.074 |
| 9 | HOVER | 0.20 | 0 | 0.00 | 73.33 | 6.59 | 1.33 | 7.71 | 38.222 |
| 10 | CLIMB | 0.04 | 0 | 152.39 | 83.33 | 7.66 | 0.32 | 1.85 | 44.428 |
| 11 | CRUISE | 0.47 | 15 | 32.00 | 46.67 | 3.94 | 1.85 | 10.71 | 22.852 |
| 12 | DESCENT | 0.04 | 0 | 152.39 | 43 | 3.6 | 0.15 | 0.87 | 20.88 |
| 13 | HOVER/LAND | 0.20 | 0 | 0.00 | 73.33 | 6.59 | 1.33 | 7.71 | 38.222 |
| | FUEL RESERVE 10% | | | | | | | | |
| | | | | | | TOTAL FUEL USED | 10 | 58 | gallons |
| | | | | | | | | | lbs |
| | | | | | | with reserve | 11 | 64 | gallons |
| | | | | | | with reserve | | | lbs |
| | TOTAL DISTANCE (Km) | | 30 | | | | | | |
| | TOTAL TIME (hr) | 4.08 | | | | | | | |

Table 9: Baseline Mission Profile

MISSION SIMULATION - UHV DESIGN

Worst Case Mission Profile

Fuel (lb/gal) **5.8**

| | Altitude | 500 ft |
| --- | --- | --- |
| | Start Elevation | 4000 ft |
| | VROC | 200 ft/min |

| SEGMENT # | DESCRIPTION | TIME (hr) | DISTANCE (Km) | AIRSPEED (Km/hr) | %Required Power | FCR (gallons/hr) | (gallons) | (lb) | FCR (lb/hr) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | WARM UP/IDLE | 0.08 | 0 | 0.00 | 7 | 0.53 | 0.04 | 0.26 | 3.074 |
| 2 | HOVER | 0.20 | 0 | 0.00 | 100 | 9.44 | 1.90 | 11.04 | 54.752 |
| 3 | CLIMB | 0.04 | 0 | 152.39 | 100 | 9.44 | 0.39 | 2.28 | 54.752 |
| 4 | CRUISE | 0.47 | 15 | 32.00 | 100 | 9.44 | 4.43 | 25.67 | 54.752 |
| 5 | DESCENT | 0.04 | 0 | 152.39 | 100 | 9.44 | 0.39 | 2.28 | 54.752 |
| 6 | HOVER/LAND | 0.20 | 0 | 0.00 | 100 | 9.44 | 1.90 | 11.04 | 54.752 |
| 7 | GROUND (ELECTRICAL) | 2.00 | 0 | 0.00 | | | | | |
| 8 | WARM UP/IDLE | 0.08 | 0 | 0.00 | 7 | 0.53 | 0.04 | 0.26 | 3.074 |
| 9 | HOVER | 0.20 | 0 | 0.00 | 100 | 9.44 | 1.90 | 11.04 | 54.752 |
| 10 | CLIMB | 0.04 | 0 | 152.39 | 100 | 9.44 | 0.39 | 2.28 | 54.752 |
| 11 | CRUISE | 0.47 | 15 | 32.00 | 100 | 9.44 | 4.43 | 25.67 | 54.752 |
| 12 | DESCENT | 0.04 | 0 | 152.39 | 100 | 9.44 | 0.39 | 2.28 | 54.752 |
| 13 | HOVER/LAND | 0.20 | 0 | 0.00 | 100 | 9.44 | 1.90 | 11.04 | 54.752 |
| | FUEL RESERVE 10% | | | | | | | | |
| | | | | | | | | | |
| | TOTAL DISTANCE (Km) | 30 | | | | TOTAL FUEL USED | 18 | 105 | gallons / lbs |
| | TOTAL TIME (hr) | 4.08 | | | | with reserve | 20 | 116 | gallons / lbs |

Table 10: Worst Case Mission Profile

## C2 – Power Generation

> *Fuel Cells*

o *Presentation*

The theory of the fuel cell technology was elaborated in 1802, but fuel cells have only been developed for a few decades. Car manufacturers are now very confident in this technology, thus they are funding many researchers in order to install fuel cells in their vehicles the soonest as possible. But fuel cells have shown there efficiency in NASA's programs, such as NASA's Space Shuttle Orbiter where they have provided electrical power. Fuel cells are a promising long-term technology. That is the reason why we propose to use fuel cells in some of our concepts.

o *Technical description*

In a fuel cell, hydrogen reacts with oxygen from the air in such a way that that a voltage is generated between two electrodes. A proton-exchange membrane let the hydrogen protons pass, while electrons are deviated to produce electricity. Then, the hydrogen protons and the corresponding electrons are combined with oxygen from the air, to form water. Heat is produced during this chemical reaction.

By using hydrogen, the problem is to store the fuel. It is also possible to use hydrocarbons to fuel the cell, which will then produce some carbon dioxide as well. But before being used into the cell, it is necessary to reform the hydrocarbon. This adds weight and complexity. So the technology proposed is the Proton-Exchange-Membrane Fuel Cell, running on hydrogen.
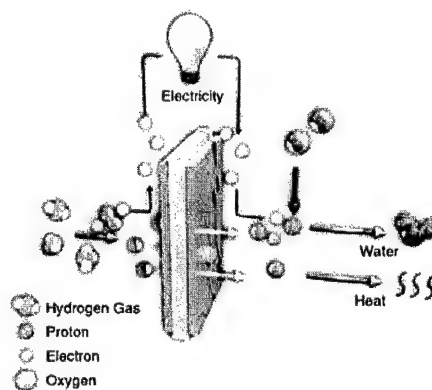


Unless batteries, fuel cells are almost endlessly rechargeable: they only need some fuel. Some of the other benefits and inconvenient are summarized below:

| Pros | Cons |
|---|---|
| 40% < yield < 50%<br>High power density<br>Noiseless<br>No moving parts<br>Maintainability<br>Reliability<br>Environmental friendly | Hydrogen storage and supply<br><br>Constant improvement of the technology, thus it is hard to figure out its state of the art at the good time. |

   o   *Sizing*

A fuel cell stack was studied to provide power to ground (10.1 kW) and avionic (2.2 kW) systems during the ground phase (2h). The following figures are realistic for a 2003 target. But within a few years, the technology is going to skyrocket. So 2012 figures will far exceed these ones.

Here are the calculations leading to our final dimensioning. The energy provided by a PEM fuel cell with 1kg of hydrogen is : $Es = 33$ kWh/kg. The efficiency of such a cell is : $40\% < \rho < 50\%$. So if E is the output energy of the cell, the required energy Er for the fuel cell is : $Er = E / \rho$. Thus the hydrogen mass is : $mH2 = Er / Es$.

Under current conditions (1 bar, 15°C), this mass corresponds a volume V : $V = mH2 / MH2 * Vm$ , where : $Vm = 24$ L/mol and $MH2 = 2$ g/mol.

Numeric results are summed up in this Excel table:

| Es (kWh/kg) | $P_{Ground}$ (KW) | $P_{Avionics}$(KW) | P (kW) | E (kWh) | ρ (%) | Er (kWh) | mH2 (kg) | V (L) @ 1bar, 15°C |
|---|---|---|---|---|---|---|---|---|
| 33,00 | 3,3 | 2,20 | 5,50 | 11,00 | 45,00 | 24,44 | 0,74 | 8888,89 |

So at 1 bar, this volume is quite superior to our UHV volume! It is thus necessary to compress the gas. But compressing the gas means skyrocketing the tank mass. Plus tank manufacturers are submitted to structure limits.

Composites Aquitaine, a French company dealing with gas tanks is testing a 28L-700bar tank. It is made out of composite materials, this is why it is light: 18kg. So using a 700bar tank is a realistic target for 2003. With these figures, masses and volumes of the tank are :

| V (L) at 1bar, 15°C | V (L) at 700bars, 15°C | Tank mass (kg) |
|---|---|---|
| 8888,89 | 12,70 | 8,16 |

Concerning fuel cell stacks, specific power is targeted to be 1kW/kg.

Concerning fuel cell accessories, specific power is 5kW/kg.

Thus final results are:

| Fuel mass (kg) | Fuel cell stack mass (kg) | Accessories mass (kg) | Total mass (kg) |
|---|---|---|---|
| 0,74 | 5,5 | 22 | 36,40 |
| Fuel volume (L) | Fuel cell stack volume (L) | Accessories volume (L) | Total volume (L) |
| 12,70 | 5,50 | 11 | 29,20 |

Here are the main characteristics of the fuel cell:

- Performance        5.50kW for 2 hrs

- Volume        29.2L

- Weight        36.4kg=80lbs

- Fuel        Hydrogen

Fuel cells seem to be the future of electric supplies. Many organizations, companies and colleges are enhancing their knowledge of this technology thanks to research projects. Thus, this technology is skyrocketing, and primarily its transportation applications. Fuel cell seem to be the promising long term technology.

For this reason, the figures given for a 2003-target, will be far exceeded by 2012-figures. Tank manufacturers are trying to increase the tank-limit-pressure, fuel cell manufacturers are decreasing accessories mass and volume,...

According to the industry's targets for 2012, here is what we should obtain. We considered a pressure limit at 900 bar for the tank, a reduction by 2 of the accessories mass and volume (due to either an improvement of the accessories' technology or a simplification of the stack).

| Tank mass (kg) | Fuel mass (kg) | Fuel cell stack mass (kg) | Accessories mass (kg) | Total mass (kg) |
|---|---|---|---|---|
| 6,35 | 0,74 | 2,75 | 11 | 20,84 |
| | Fuel volume (L) | Fuel cell stack volume (L) | Accessories volume (L) | Total volume (L) |
| | 9,88 | 3,67 | 5,5 | 19,04 |

Thus the 2012 expected characteristics:

- Performance        5.50kW for 2 hrs

- Volume        19L

- Weight        20.8kg=46lbs

- Fuel        Hydrogen

- Cost        50$/kW => 275$

So we have here a case for fuel cells. As it is a plug and play technology, we just have to think smartly to the integration of the cell. Then we will only have to use the available fuel cell.

> *Ultracapacitor*

Capacitors are a 100-year-old technology. But ultracapacitor are a new energy storage technology ideally suited for applications needing repeated bursts of power (for fractions of a second to several minutes).

To make power available when needed by the application, ultracapacitor charges power from any energy source (fuel cell, regenerative braking,...). This power is then discharged from the ultracapacitor at rates demanded by the application. The ultracapacitor can be repeatedly charged and discharged at rates optimized for the application. It allows the entire system to be tailored to optimally meet both power and energy requirements.

o *Technical description*

Ultracapacitor is a double-layer capacitor incorporating a unique metal/carbon electrode and an advanced non-aqueous electrolytic solution. As a potential is applied across the terminals, ions migrate to the high surface area electrodes. The combination of available surface area and proximity to the current collector provide an ultra-high capacitance for this electrostatic process.
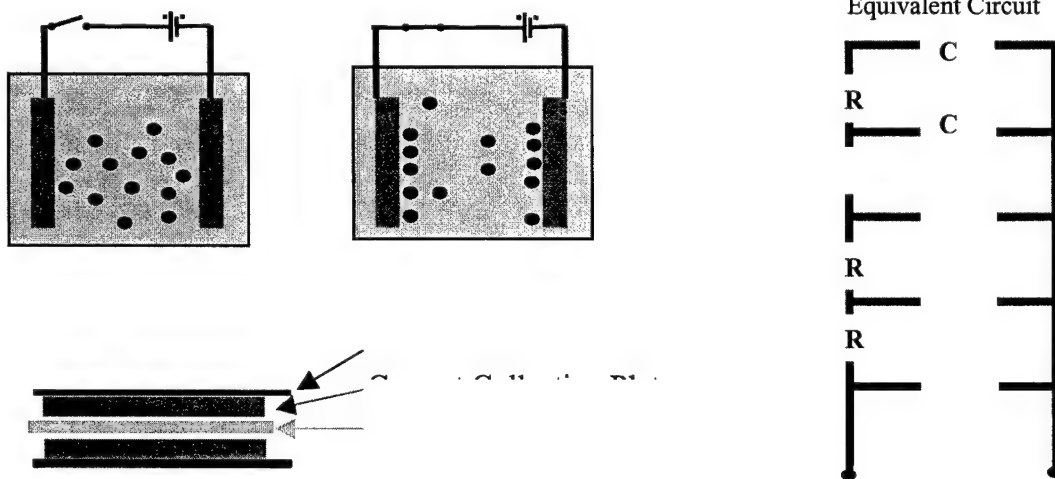


An ultracapacitor gets its area from a porous carbon-based electrode material. The porous structure of this material allows its surface area to approach 2000 m²/g, much greater than can be accomplished using flat or textured films and plates. An ultracapacitor's charge separation distance is determined by the size of the ions in the electrolyte, which are attracted to the charged electrode. This charge separation (less than 10 Å) is much smaller than can be accomplished using conventional dielectric materials. The combination of enormous surface

area and extremely small charge separation gives the ultracapacitor its outstanding capacitance relative to conventional capacitors.

Capacitors are superior to batteries with respect to energy density, longevity, and performance.
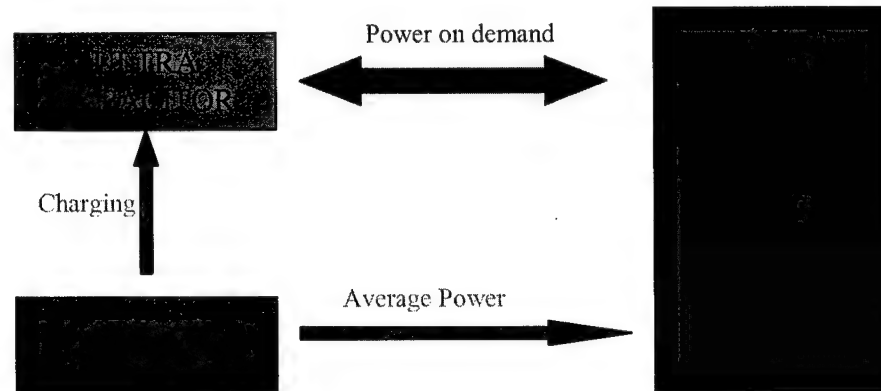


Moreover, integration of ultracapacitors into our UHV allows for a slower transient response from the prime generator (fuel cell for instance) and thus, a fuel economy.

Furthermore, ultracapacitors can be a lifetime subsystem, withstand wide temperature ranges, require little maintenance, and be placed more optimally for vehicle ergonomics.

 o  *Sizing*

Our dimensioning is based on discharges. A ultracapacitor is equivalent to a capacitor and a resistance in series. Thus the electric equation is :

$$dV = i*dt/C + i*R$$

dV represents the change in voltage during the discharge of the capacitor : $dV=V_w-V_{min}$, where $V_w$ is the operating voltage at the beginning of a discharge, and $V_{min}$ the minimum voltage allowed by the system.

We assume a constant current during the discharge of the capacitor. So we use the average current for this value (averaging of ($I_{min} = P/V_{max}$) and ($I_{max} = P/V_{min}$) where P represents the power to provide).

The duration of the discharge pulse is dt.

C is the capacitance of the complete ultracapacitor stack at its operating point. This value is based on the number of individual capacitors in series or parallel :

$$C = C_{cell} * N_{parallel} / N_{series} = C_{cell} * N_{parallel} / V_{max}/V_{cell}$$

Where $V_{cell} \sim 2.3V/cell$

R is the resistance of the complete ultracapacitor stack, also based on the number of individual capacitors in series or parallel:

$$R = R_{cell} * N_{parallel} / N_{series} = R_{cell} * N_{parallel} / V_{max}/V_{cell}$$
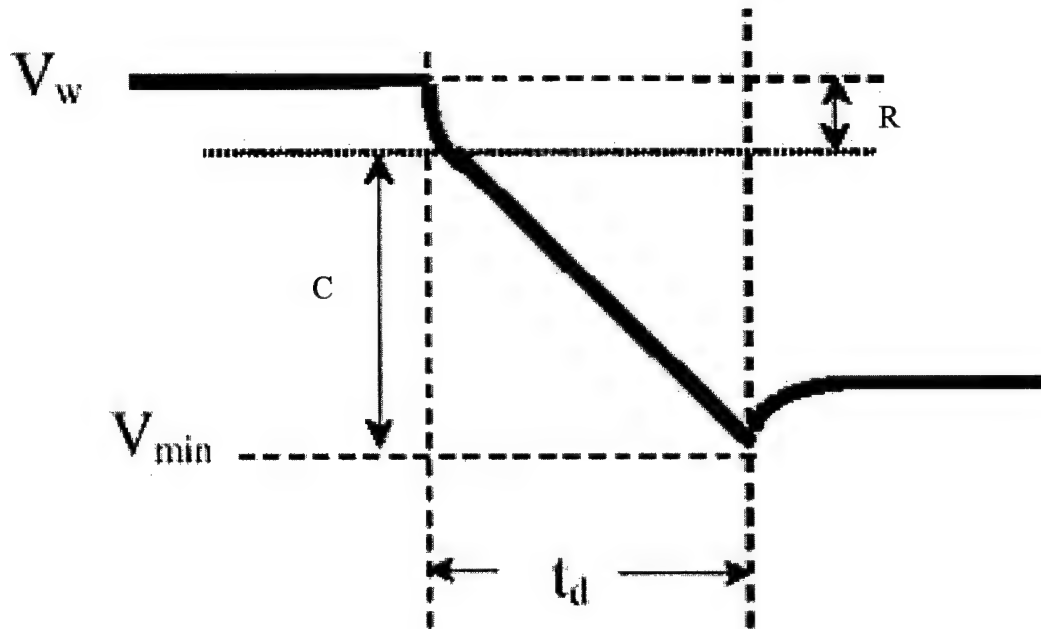


Discharge Profile

So, in order to dimension the ultracapacitor, we need to determine basic system parameters. In the worst scenario, our application requires a peak of power of $P_{max}$ during dt.

$V_{max} = 48$ V

$V_w = 24$ V

$V_{min} = 12$ V

$P_{max} = 6$ kW

$dt = 6.5$ s

Thus $dV = 24 - 12 = 12$ V

$i = (6000/48+6000/12)/2 = 312.5$ A

With this range of figures, the best ultracapacitor should be a PC2500 (2500F). Thus, knowing the number of cells in series, we can figure out the total stack capacitance.

$N_{series} = 48 / 2.3 = 20.9$ cells          So we will use 21cells in series.

C = 2500 / 21 = 119 F

For this ultracapacitor, the cell resistance is 0.001 $\Omega$, thus, the total stack resistance R is : R = 0.001*21 = 0.021$\Omega$.

We can now solve the previous equation:

dV = i*dt/C + i*R = 312.5 * 6.5/119+ 312.5* 0.021 = 23V

Our original requirement allowed a voltage change of dV=12V, and the solution provides dV=23V. So we have 200% of the allowed voltage drop. Since the equations are simple linear relationships, the optimum ultracapacitor would be 200% the size of a PC2500.

Thus, we will use two PC2500 in series. This solution also allows us to get a good redundancy for the starting of the engine. In fact, to start the engine, we will use one of both ultracapacitors. We will load each of them before the mission, with the help of the ground station.

Considering the current used, we also evaluated the diameter of the electric lines. Usually a 10A current corresponds to a 1 mm$^2$ section. Thus our most important diameter will be 9mm. This is a reasonable value and of course, it can be reduced by using a better heat exchanger,…. So we do not have to worry about this parameter.

Here are the main characteristics of the ultracapacitor:

- Manufacturer                     Maxwell

- Name                             PC2500

- Capacitance                      2500 F

- Rated Current                    625 A

- Size                             161mm*61.5mm*61.5mm

- Weight                           0.725kg=1.60lbs

- Operating Temperatures           -40°C / 70°C
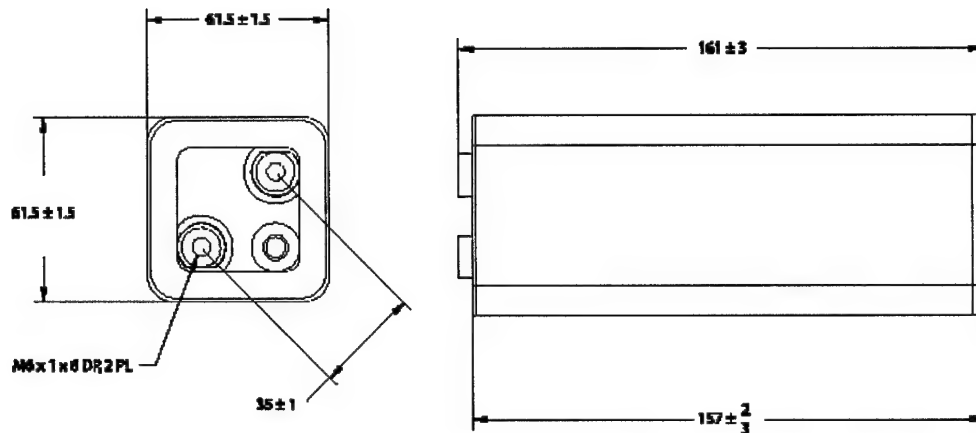
Dimensions (in mm) of the Maxwell PC 2500 ultracapacitor

> ➤ *ICE configuration*

   o *Chart*
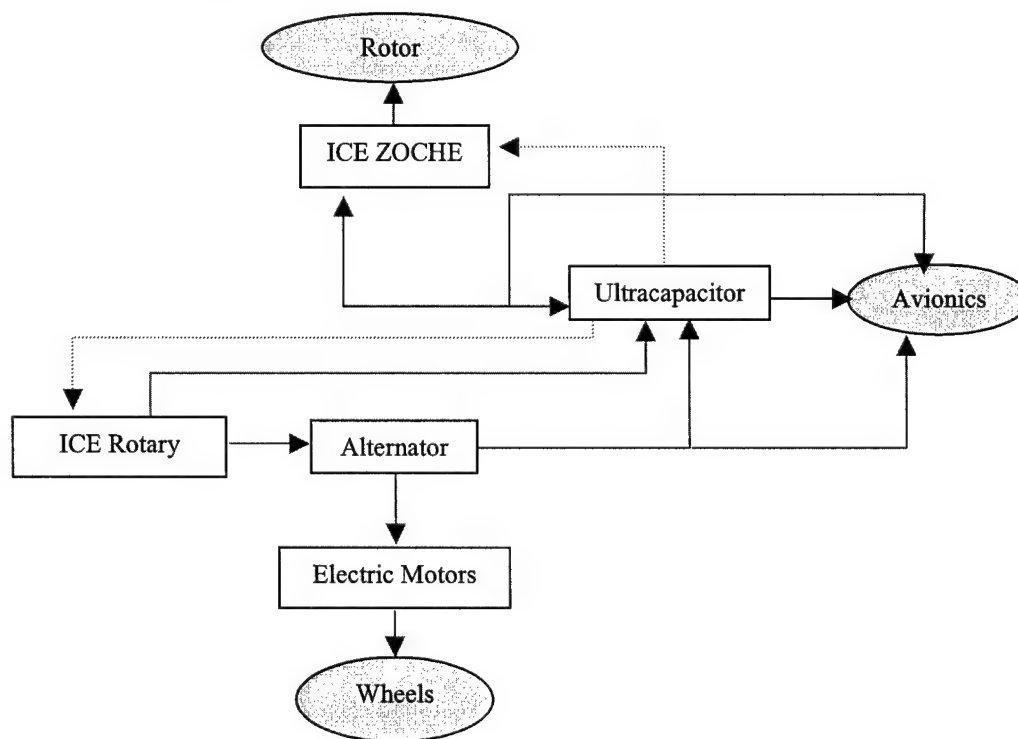


To power the rotor, we use the 2-stroke engine (Zoche engine). To start the engine, we use the ultracapacitor. As this engine has its own alternator, we can use it directly to reload the ultracapacitor during the flight, and power the avionics.

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Then for the ground part, we switch off the Zoche engine and we start the rotary engine with the ultracapacitor. As this engine does not have its own alternator, we have to use one. For the wheels we use four little electric engines. To power those engines, the avionics, and to reload the battery, we use the rotary engine.

Here is the total weight of this ICE configuration. The dimensioning that follows helped us to build this Excel table.

| | | | |
|---|---|---|---|
| ICE zoche | Dry Weight | 184.8 lbs | 84 kg |
| | Oil | 17.6 lbs | 8 kg |
| Rotary | Dry Weight | 83.6 lbs | 38 kg |
| | Oil | 11 lbs | 5 kg |
| Air and Ground Transmission | Weight | 88 lbs | 40 kg |
| Alternator *2 | Weight | 55.44 lbs | 25.2 kg |
| Electric Motors*4 | Weight | 52.8 lbs | 24 kg |
| Ultracapacity *2 | Weight | 3.3 lbs | 1.5 kg |
| TOTAL WEIGHT | | 497 lbs | 226 kg |
| 45.14% of 1100 lbs | | | |

o   Rotary Engines

The rotary engine is sometimes called a Wankel engine. It is different from classical piston engines by the fact that they do not use an alternative system. All the rotary engines have nearly the same characteristics.

The heart of a rotary engine is the rotor. This rotor is the equivalent of the pistons in a piston engine. The rotor is mounted on a large circular lobe on the output shaft. As the rotor orbits inside the housing, it pushes the lobe around in tight circles, turning three times for every one revolution of the rotor. As the rotor moves through the housing, the three chambers created by the rotor change size. This size change produces a pumping action.

When the combustion starts, there is an increasing of pressure, which force the rotor to move. The rotor follows a special path. This path keeps each of the three peaks of the rotor in contact with the stator, creating three separate volumes of gas. As the rotor moves around the chamber, each of the three volumes of gas alternatively expands and contracts. It is this expansion and contraction that compress it and makes useful power as the gases expand and then expels the exhaust.

On rotary engine, each of the three faces of the rotor is working on one part of the cycle. So in one complete revolution of the rotor, there will be three combustion strokes. There is one combustion stroke for each revolution of the output shaft.

A rotary engine uses less moving parts than a classical engine, so it is lighter and smaller. Moreover, as there is no alternative movement, movement is smoother and vibrations are reduced. The vibration of air cells creates noise. So if we can reduce the number of moving parts, and the amplitude of the vibration, there will be lower noise emission.

Wankel engines are very interesting because of their low noise emission in comparison with a classical stroke engine. We have looked for Wankel engines and it seems that the most powerful diesel rotary engine we can get for the moment does not go over 20 hp. So, we could use this kind of engine for the ground power only.

Rotary engines seem to be feasible for the moment only for little power. We have found a rotary engine, manufactured by *Wankel Rotary*, a German company. We could use this engine for the ground propulsion. Here are the specifications of this engine:

- Manufacturer            Wankel

- Name                LOCR 407 SD

- Size                  404mm*388mm*399mm

- Weight             38kg=83.6lbs

- Performance         16hp=12kW @3600rpm

- Fuel Consumption    330g/kWh

- Fuel                 Diesel / JP4 / JP8

> *Transmission work*

  o *Air transmission*

This transmission system fits for both configurations.

The aim of the transmission system is to transmit and distribute mechanical power. Designs have been accomplished keeping in mind reliability, maintainability, efficiency and weight.

Our air transmission system constitutes an important element in the UHV, because it transmits the power coming from the air engine to both rotors.

This system is sized in order to support the UHV's maximum lift forces during the climbing because it is the worst load case for this system. The rotor shaft speed is fixed at 830 RPM and the maximum Zoche engine shaft speed is fixed at 2500 RPM. The maximum power used for the transmission calculations is 150hp. The position of the Zoche Engine is supposed to be horizontal.

This system has to support the maximum constraints due to the maximum engine torque. The other parts like axis or bearings have to support the UHV loads with a minimum deformation in order to run correctly. Conic gears as the other components will be sized according to the maximum constraints.

The system configuration is similar to the one above, but the planetary gear train and the distributor are removed. Another conic gear is inserted in the system.

We sized a light, low noisy, simple and efficient device, in order to get the more reliable transmission system as possible.

> Main characteristics of the gear box
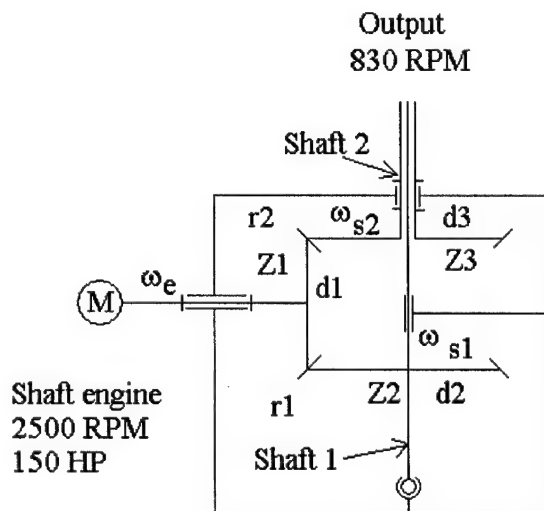


Output
830 RPM

Shaft 2

$r2$  $\omega_{s2}$  $d3$
$Z1$  $Z3$
$d1$

$\omega_e$  (M)

$\omega_{s1}$

Shaft engine
2500 RPM
150 HP

$r1$  $Z2$  $d2$

Shaft 1

*Zn is the number of teeth of the conic gear n,*
*r1 and r2 are the reductions ratios,*
*dn is the pitch diameter of the gear n,*
*$\omega_e$ is the shaft speed input,*
*$\omega_{s1}$ is the shaft speed output for the rotor 1,*
*$\omega_{s2}$ is the shaft speed output for the rotor 2.*

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*Figure 3: Data of the three conics gears configuration*

Reduction ratio :

$$\frac{\omega_{S2}}{\omega_e} = r_2 \quad \frac{\omega_{S1}}{\omega_e} = r_1 \quad \text{but} \, \omega_{S2} \cong -\omega_{S1} \, \text{thus,} \, |r_2| = |r_1|$$

With a high efficiency of the gears, the power in the output should be the same.

According to the specifications, $|r1| = |r2| = 830/2500 = 0.332$

In order to get this ratio, we can choose d1=100mm and d2=d3=300mm. Thus the ratio d1 by d2 or d3 will be about 0.33.

Sizing of the conics gears 1,2 and 3 :

Then we have to determine the tangential force, Ft, on the teeth of the gear. If Pm is the maximum power of the shaft engine and, the torque C on the shaft is about:

$$Pm = C \times \omega e \qquad C = \frac{Pm}{\omega e} = \frac{150 \times 746}{2500 \times \frac{2 \times \pi}{60}} = 427.4 N.m$$

Thanks to those figures, we can get the best gears meeting our needs. The type of gears chosen will be spiro-conic co-current. These gears decrease the noise of the system and present a good mechanical resistance.

Here are the main characteristics of the gears:

- Pitch diameter          D1 = 180 mm       D2 = D3= 58.065 mm

- Teeth number            N1 = 10      N2 = N3 = 32

- Pressure Angle          20°

- Average Spiral Angle     35°

- Quality of manufacturing    6/7 (DIM norm)

- Materials               18 NC 13

Shaft diameters are sized in order to avoid flexions, compressions constraints that would involve deformations. Those ones should be harmless to the functioning of the system. Thus, the shaft engine has a diameter of 40 mm, shaft 1, 65 mm and shaft 2 has an outside diameter of 100 mm and an inside diameter of 75 mm.

Bearings

Bearings drive the different axis, with the minimum frictions as possible. They also have to support axis and radius loads. The main rule of the bearings design consists in using

one bearing fixed on each shaft and the other one have to be free. This rule is due to manufacturing constraints. For the shaft engine, a two-ball-row bearing should be used, because it will be able to support important axis and radial loads during high speeds.

For shaft 1, because they support very important axial loads, two roller bearings will be used: the first one at the base of the shaft and the other one set up in opposition with the first one.

For shaft 2, only one bearing is designed, but on the plan another one will be just outside the shaft. They will have the same characteristics than the shaft ones. The dimensions are different.

Miscellaneous

In order to set up correctly the gears on the shafts, sprockets have been sized resist to the maximum power defined above. Concerning the other parts, they have been studied to reduce to the minimum the power while conserving a high load resistance.

Flow oils should be studied to optimize the lubrication. It will be made by bubbling with an EP 80 oil (extreme pressure oil 1/4V).

The set up of the transmission box on the UHV structure can be realized thanks to 3 joints (not shown on this CATIA drawing).
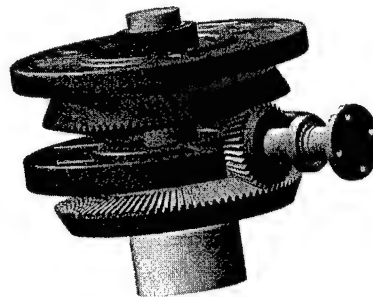


This first approach of the study of the air transmission system of the UHV was very important because it has helped us to have an idea about its main characteristics as dimensions and weight.

Sizing :

- Diameter           360 mm

- Width             330 mm

- Weight          35 kg = 77lbs

To conclude, this gearbox will meet the UHV needs. It should be reliable, light, low noisy and easy to maintain. To improve it, it could be interesting to use numerical analysis

with FEM in order to localize the concentration constraints. Thus, its design should be improved and so should its weight.

> *Ground transmission*

The ground transmission should be used in the ICE configuration only. The ICE supplies power to the alternators thanks to a transmission system. They convert mechanical power into electric power. They have to provide enough power to the different electric parts: ground and avionics systems.

In order to transmit power, the transmission system will have to multiply the engine shaft speed. The maximum power delivered by the alternators is 4,200W at 5,000 RPM. The ICE can deliver a maximum power of 12kW at 3600 RPM. Thus, the use of two alternators should meet the power requirements.

In order to size this gearbox, hypothesis concerning the motor specifications has been made. The cruise speed is supposed to be at 3,000 RPM delivering 12HP. Concerning the output of the multiplication gear, the maximum shaft speed is fixed at 5,000 RPM. The reduction ratio is 5:3.
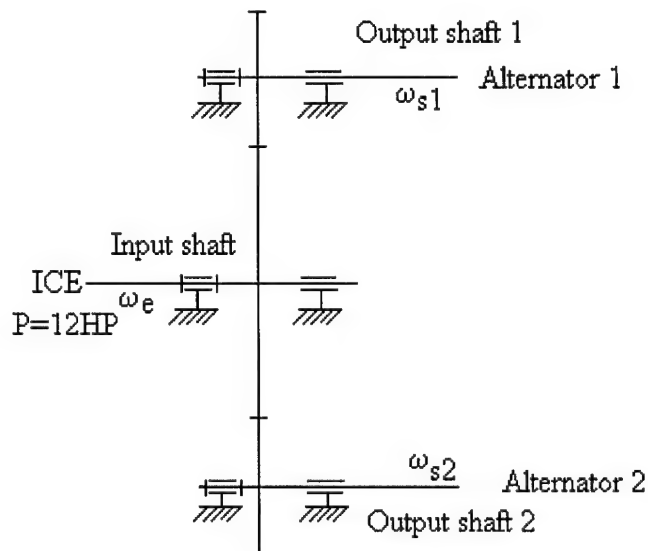


This system will be sized with the same aim and ISO methods in order to reduce weight to the minimum, with the highest efficiency and reliability.

Sizing of the gears

Firstly, we have to determine the tangential force, Ft, on the teeth of the gear. If P is the power of the shaft engine, the torque C gets on the shaft is about:

$$P = C \times \omega e$$

$$C = P / \omega e = (12 \times 746) / (3000 \, (2 \, \pi/60)) = 28.5 \text{ N m}$$

The tangential force on the pitch radius (d1/2) of the gear may be determined with the following relation:

$$Ft = 2 \times C / d1 = 427.4 / (75 * 1e-3/2) = 380 \text{ N}$$

The gear modulus is expressed by:

$$m > 2.34 * \text{sqrt} (Ft / (k \times Rpe)) \qquad \text{where } m = p/\pi$$

with        Rpe = 466.7 MPa

        k, the coefficient of the teeth width is fixed at 10

Numerical Application:

m> 2.34 * sqrt (380/(10*466.7)) = 0.67mm

We will choose m=2 mm

Thus Z1=75 teeth and Z2=Z3=45 teeth.

As the torque is relatively small compared to the gear characteristics, the ISO criteria are validated. After having calculated the main gear parameters, (gear modulus m,...) the main characteristics of each conic gear can be determined :

- Modulus                 m1=2 mm

- Teeth number            Ze=75              Zs=45

- Pitch diameter          de=150 mm          ds=90 mm

- Covering / hollow       ha=2 mm            hf=2.5 mm

- Outside diameter        dae=154 mm         das=145 mm

- Inside diameter         dfe=145 mm         dfs= 85 mm

- Face width              b=20 mm

The three shafts are driven by ball bearings. For each shaft, we have to set up two bearings. For the shaft engine, we should use the following bearings:

Characteristics of the engine shaft:

- Manufacturer and type        SKF ball bearings Type BC serial size 10

- Inside Diameter          d=25 mm

- Outside Diameter        D=47 mm

- Max Rotation Speed     Nmax = 18,000 RPM

Characteristics of the other shafts:

- Manufacturer         SKF two-row-ball bearings Type BE serial size 32

- Inside Diameter      d=12 mm

- Outside Diameter    D=47 mm

- Max Rotation Speed  Nmax = 8,000 RPM

The following drawing shows the ground gearbox. The yellow gear and shaft are linked to the ICE. The two others are directly joined to each alternators.
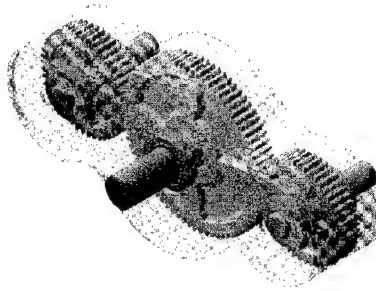


*Figure: Drawing of the ground transmission*

This gearbox should be a good solution for this ground propulsion system because it saves weight and increases the efficiency of the UHV. An improvement should consist in putting helicoidally gears instead of these. This would reduce noise but increase costs…

- Weight of the ground transmission:      5kg (11 lbs)

C3 – Aerodynamics

# Choctaw Power Estimations for Forward Flight

| W(lbs)= | b= | R(ft)= | A(ft^2)= | RPM= | Rho(sl/ft^3)= | Vtip(ft/sec)= | Cd0= | D/q(ft^2)= | Ct= | C(ft)= | Sigma= |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1100 | 2 | 7.5 | 176.7145 | 827.6064 | 0.00209 | 650 | 0.0104 | 16.22 | 0.007049 | 0.416666 | 0.035367 |

Co-Axial

| Velocity.Kt | Mu | Cpi | Pi | Cp0 | P0 | Cpp | Pp | Cp | HP |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 0.01294 | 4.01159 | 73.9797 | 4.60136 | 8.48558 | 9.95442 | 0.01835 | 4.47272 | 82.4836 |
| 15 | 0.03883 | 3.65065 | 67.3234 | 4.62971 | 8.53787 | 2.68769 | 0.49565 | 4.14050 | 76.3569 |
| 25 | 0.06472 | 3.06218 | 56.4711 | 4.68641 | 8.64244 | 1.24430 | 2.29467 | 3.65525 | 67.4082 |
| 35 | 0.09061 | 2.47063 | 45.5620 | 4.77147 | 8.79929 | 3.41437 | 6.29659 | 3.28921 | 60.6579 |
| 45 | 0.11650 | 2.00610 | 36.9955 | 4.88487 | 9.00843 | 7.25677 | 13.3825 | 3.22027 | 59.3865 |
| 55 | 0.14239 | 1.66829 | 30.7657 | 5.02663 | 9.26985 | 1.32493 | 24.4337 | 3.49588 | 64.4693 |
| 65 | 0.16828 | 1.42140 | 26.2126 | 5.19674 | 9.58356 | 2.18699 | 40.3312 | 4.12806 | 76.1275 |
| 75 | 0.19416 | 1.23590 | 22.7917 | 5.39520 | 9.94955 | 3.35962 | 61.9563 | 5.13503 | 94.6976 |
| 85 | 0.22005 | 1.09234 | 20.1443 | 5.62201 | 10.3678 | 4.89061 | 90.1900 | 6.54515 | 120.702 |
| 95 | 0.24594 | 9.78273 | 18.0408 | 5.87718 | 10.8383 | 6.82774 | 125.913 | 8.39373 | 154.792 |
| 105 | 0.27183 | 8.85596 | 16.3317 | 6.16069 | 11.3612 | 9.21879 | 170.008 | 0.00107 | 197.701 |

| Velocity (ft/s) | HP |
|---|---|
| 8.439 | 82.4836 |
| 25.317 | 76.3569 |
| 42.195 | 67.4082 |
| 59.073 | 60.6579 |
| 75.951 | 59.3865 |
| 92.829 | 64.46932 |
| 109.707 | 76.12752 |
| 126.585 | 94.69769 |
| 143.463 | 120.7022 |

| | 160.341 | 154.7928 |
|---|---|---|
| | 177.219 | 197.7011 |

# Choctaw Power Estimations for Hover and Minimum Climb

| Diameter (m) | Diameter (ft) | Area | Induced Power | 2(FM = .8) | Hover Power (HP) | Total Power | Power for Min Climb (HP) |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 0.1524 | 0.5 | 0.018241 | 610561.9908 | 1526404.977 | 2886.189343 | 1644.220899 | 2897.939334 |
| 0.3048 | 1 | 0.072965 | 305280.9954 | 763202.4885 | 1443.094671 | 825.44378 | 1454.844662 |
| 0.4572 | 1.5 | 0.164173 | 203520.6636 | 508801.659 | 962.0631142 | 552.5180739 | 973.8131052 |
| 0.6096 | 2 | 0.291863 | 152640.4977 | 381601.2443 | 721.5473357 | 416.0552208 | 733.2973266 |
| 0.762 | 2.5 | 0.456036 | 122112.3982 | 305280.9954 | 577.2378685 | 334.1775089 | 588.9878595 |
| 0.9144 | 3 | 0.656692 | 101760.3318 | 254400.8295 | 481.0315571 | 279.5923677 | 492.7815481 |
| 1.0668 | 3.5 | 0.893831 | 87223.14155 | 218057.8539 | 412.3127632 | 240.6029811 | 424.0627542 |
| 1.2192 | 4 | 1.167454 | 76320.24885 | 190800.6221 | 360.7736678 | 211.3609412 | 372.5236588 |
| 1.3716 | 4.5 | 1.477559 | 67840.2212 | 169600.553 | 320.6877047 | 188.6171323 | 332.4376957 |
| 1.524 | 5 | 1.824146 | 61056.19908 | 152640.4977 | 288.6189343 | 170.4220852 | 300.3689252 |
| 1.6764 | 5.5 | 2.207217 | 55505.63553 | 138764.0888 | 262.3808493 | 155.5352285 | 274.1308403 |
| 1.8288 | 6 | 2.626771 | 50880.1659 | 127200.4148 | 240.5157786 | 143.1295146 | 252.2657695 |
| 1.9812 | 6.5 | 3.082808 | 46966.30699 | 117415.7675 | 222.0145648 | 132.6323721 | 233.7645558 |
| 2.1336 | 7 | 3.575327 | 43611.57077 | 109028.9269 | 206.1563816 | 123.6348213 | 217.9063726 |
| 2.286 | 7.5 | 4.104330 | 40704.13272 | 101760.3318 | 192.4126228 | 115.836944 | 204.1626138 |
| 2.4384 | 8 | 4.669816 | 38160.12443 | 95400.31107 | 180.3868339 | 109.0138013 | 192.1368249 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2.5908 | 8.5 | 5.271784 | 35915.41122 | 89788.52806 | 169.7758437 | 102.9933814 | 181.5258346 |
| 2.7432 | 9 | 5.910236 | 33920.1106 | 84800.2765 | 160.3438524 | 97.64189692 | 172.0938433 |
| 2.8956 | 9.5 | 6.585170 | 32134.84162 | 80337.10406 | 151.9047022 | 92.85372664 | 163.6546932 |
| 3.048 | 10 | 7.296587 | 30528.09954 | 76320.24885 | 144.3094671 | 88.54437338 | 156.0594581 |
| 3.2004 | 10.5 | 8.044487 | 29074.38052 | 72685.95129 | 137.4375877 | 84.64543473 | 149.1875787 |
| 3.3528 | 11 | 8.828871 | 27752.81776 | 69382.04441 | 131.1904247 | 81.10094503 | 142.9404156 |
| 3.5052 | 11.5 | 9.649737 | 26546.17351 | 66365.43379 | 125.4864932 | 77.86467184 | 137.2364841 |
| 3.6576 | 12 | 10.50708 | 25440.08295 | 63600.20738 | 120.2578893 | 74.89808808 | 132.0078802 |
| 3.81 | 12.5 | 11.40091 | 24422.47963 | 61056.19908 | 115.4475737 | 72.16883101 | 127.1975647 |
| 3.9624 | 13 | 12.33123 | 23483.15349 | 58707.88373 | 111.0072824 | 69.6495168 | 122.7572734 |
| 4.1148 | 13.5 | 13.29803 | 22613.40707 | 56533.51767 | 106.8959016 | 67.31681846 | 118.6458925 |
| 4.2672 | 14 | 14.30131 | 21805.78539 | 54514.46347 | 103.0781908 | 65.15074143 | 114.8281818 |
| 4.4196 | 14.5 | 15.34107 | 21053.86175 | 52634.65438 | 99.52377044 | 63.13404902 | 111.2737614 |
| 4.572 | 15 | 16.41732 | 20352.06636 | 50880.1659 | 96.20631142 | 61.25180277 | 107.9563024 |
| 4.7244 | 15.5 | 17.53005 | 19695.54809 | 49238.87023 | 93.10288202 | 59.49099176 | 104.852873 |
| 4.8768 | 16 | 18.67926 | 19080.06221 | 47700.15553 | 90.19341696 | 57.84023144 | 101.9434079 |
| 5.0292 | 16.5 | 19.86496 | 18501.87851 | 46254.69627 | 87.46028311 | 56.2895172 | 99.21027407 |
| 5.1816 | 17 | 21.08713 | 17957.70561 | 44894.26403 | 84.88792184 | 54.83002145 | 96.6379128 |

**C5: Programmatics**

# Wire Diagram WBS

**Level 1**

Unmanned Hybrid Vehicle

**Level 2**

- Air / Ground Vehicle
- Systems Engineering / Program Management
- System Test & Evaluation
- Training
- Data
- Peculiar Support Equipment
- Common Support Equipment
- Operational / Site Activation
- Industrial Facilities
- Initial Spares or Repair Parts
- Sustainment
- Disposal

**Level 3**

Air / Ground Vehicle:
- Frame
- Propulsion / Power
- Auxiliary Power
- Vehicle Application Software
- Vehicle System Software
- Automatic Flight / Steering Control
- Suspension / Steering

Systems Engineering / Program Management:
- Systems Engineering
- Program Management

System Test & Evaluation:
- Development Test & Evaluation
- Operational Test & Evaluation
- Mock-ups
- Test & Evaluation Support
- Test Facilities

Training:
- Equipment
- Services
- Facilities

Data:
- Technical Publications
- Engineering Data
- Management Data
- Support Data
- Data Depository

Peculiar Support Equipment:
- Test & Measurement Equipment
- Support & Handling Equipment

Common Support Equipment:
- Test & Measurement Equipment
- Support & Handling Equipment

Operational / Site Activation:
- System Assembly, Installation, & Checkout on Site
- Contractor Technical Support
- Site Construction
- Site / Vehicle Conversion

Industrial Facilities:
- Construction / Conversion / Expansion
- Equipment Acquisition Or Modernization
- Maintenance (Industrial Facilities)

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| LINE # | WBS LEVEL | WORK BREAKDOWN STRUCTURE ELEMENTS |
|---|---|---|
| 1.0 | 1 | Unmanned Hybrid Vehicle |
| 1.1 | 2 | Air / Ground Vehicle |
| 1.1.1 | 3 | Frame |
| 1.1.2 | 3 | Propulsion / Power |
| 1.1.3 | 3 | Auxiliary Power |
| 1.1.4 | 3 | Vehicle Application Software |
| 1.1.5 | 3 | Vehicle System Software |
| 1.1.6 | 3 | Automatic Flight / Steering Control |
| 1.1.7 | 3 | Suspension / Steering |
| 1.1.8 | 3 | Communication / Identification |
| 1.1.9 | 3 | Navigation / Guidance |
| 1.1.10 | 3 | Central Computer |
| 1.1.11 | 3 | Data Display and Controls |
| 1.1.12 | 3 | Survivability |
| 1.1.13 | 3 | Reconnaissance |
| 1.1.14 | 3 | Central Integrated Checkout |
| 1.1.15 | 3 | Auxiliary Equipment |
| 1.2 | 2 | Systems Engineering / Program Management |
| 1.2.1 | 3 | Systems Engineering |
| 1.2.2 | 3 | Program Management |
| 1.3 | 2 | System Test and Evaluation |
| 1.3.1 | 3 | Development Test and Evaluation |
| 1.3.2 | 3 | Operational Test and Evaluation |
| 1.3.3 | 3 | Mock-ups |
| 1.3.4 | 3 | Test and Evaluation Support |
| 1.3.5 | 3 | Test Facilities |
| 1.4 | 2 | Training |
| 1.4.1 | 3 | Equipment |
| 1.4.2 | 3 | Services |
| 1.4.3 | 3 | Facilities |

## C6: Work Breakdown Structure

| LINE # | WBS LEVEL | WORK BREAKDOWN STRUCTURE ELEMENTS |
|--------|-----------|-----------------------------------|
| 1.5 | 2 | Data |
| 1.5.1 | 3 | Technical Publications |
| 1.5.2 | 3 | Engineering Data |
| 1.5.3 | 3 | Management Data |
| 1.5.4 | 3 | Support Data |
| 1.5.5 | 3 | Data Depository |
| 1.6 | 2 | Peculiar Support Equipment |
| 1.6.1 | 3 | Test and Measurement Equipment |
| 1.6.2 | 3 | Support and Handling Equipment |
| 1.7 | 2 | Common Support Equipment |
| 1.7.1 | 3 | Test and Measurement Equipment |
| 1.7.2 | 3 | Support and Handling Equipment |
| 1.8 | 2 | Operational / Site Activation |
| 1.8.1 | 3 | System Assembly, Installation, and Checkout on Site |
| 1.8.2 | 3 | Contractor Technical Support |
| 1.8.3 | 3 | Site Construction |
| 1.8.4 | 3 | Site / Vehicle Conversion |
| 1.9 | 2 | Industrial Facilities |
| 1.9.1 | 3 | Construction / Conversion / Expansion |
| 1.9.2 | 3 | Equipment Acquisition or Modernization |
| 1.9.3 | 3 | Maintenance (Industrial Facilities) |
| 1.10 | 2 | Initial Spares or Repair Parts |
| 1.11 | 2 | Sustainment |
| 1.12 | 2 | Disposal |

**C7: Project Milestones**

**Determination of Mission Need**
**FY2002 – Phase 0 (Concept Exploration)**
- Statutory
  - Consideration of technology issues
  - Market research
- Regulatory
  - Validated Mission Needs Statement (MNS)
  - Analysis of multiple concepts
  - Evaluation master plan
  - Exit Criteria
  - Acquisition Decision Memorandum (ADM)

**Milestone A**

**FY2003 – Phase I (Concept and Technical Development)**
- Statutory
  - Consideration of technology issues
  - Market research
  - Acquisition Program Baseline (APB)
  - Compliance with strategic plan
  - Selected acquisition report – Major Defense Acquisition Program (MDAP) only
  - Unit cost report – MDAP only
  - Live fire waiver and alternate Live Fire Test & Evaluation (LFT&E)
  - Industrial capabilities
  - LRIP quantities
  - Independent cost estimate and man power – MDAP only
  - Cooperative opportunities
  - Clinger-Cohen Act (CCA) compliance
  - CCA certification to Congressional Defense Committees (CDC) for Major Automated Information System (MAIS)
  - Application for frequency allocation
  - National environmental policy act schedule
  - Core logistics analysis – source of repair analysis
  - Competition analysis ($3M rule)
- Regulatory
  - Validated Operational Requirements Document (ORD)
  - Acquisition strategy
  - Analysis of Alternatives (AoA)
  - System threat assessment
  - Independent technology assessment
  - Command, Control, Communications, Computers, and Intelligence Support Plan (C4ISP)
  - Affordability assessment

- Economic analysis – MAIS only
- Component cost analysis
- Cost analysis requirement description – MDAP only
- Test and Evaluation Master Plan (TEMP)
- Operational test activity report of operational test and evaluation results
- Program Protection Plan (PPP)
- Exit Criteria
- ADM

**Milestone B**

**FY2007 – Phase II (System Development & Demonstration)**
- Statutory
  - Consideration of technology issues
  - APB – Update as necessary
  - Compliance with strategic plan
  - Selected acquisition report – MDAP only
  - Industrial capabilities
  - Independent cost estimate – MDAP only
  - Cooperative opportunities
  - CCA compliance
  - CCA certification to CDC for MAIS
  - National environmental policy act schedule
- Regulatory
  - Validated Operational Requirements Document (ORD) – Reevaluate
  - Acquisition strategy
  - AoA
  - System threat analysis
  - Independent technology assessment
  - C4ISP
  - Affordability assessment
  - Cost analysis requirement description – MDAP only
  - TEMP – Update if necessary
  - Operational test activity report of operational test and evaluation results
  - PPP
  - Exit criteria
  - ADM

**Milestone C**

**FY2010 – Phase III (Production, Deployment, and Operational Support)**

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# Appendix D – Web Pages

Copies of web pages referenced in this volume are located on the "Unmanned Hybrid Vehicle" CD that was provided as a supplement to the deliverables.